last time (1)

DNS time-to-lives and limited caching

mapping MAC addresses to IP addresses

- if know IP should be on network, ask everyone "is this yours?"

DHCP: broadcast "what IP/etc. to use"

network address translation

- large set of inside IP addresses
- map to small set of outside IP addresses
- table: (remote IP+port, outside IP+port) $\rightarrow$ inside IP+port

last time (2)

security goals: confidentiality, authenticity

encryption

E(key, data) = ciphertext

cannot learn about data from ciphertext + E without key

message authentication codes

MAC(key, data) = tag

cannot find MAC(key, f(data)) without key

even with MAC(key, data), data

quiz Q1

1: A$\rightarrow$ A wifi router

2: A wifi router $\rightarrow$ B wifi router (via wired network)

3: B wifi router $\rightarrow$ B

$+$ again in reverse

$=$ 6 messages

quiz Q2/3

frame addresses: machine on current network

packet address: ultimate (multi-step) destination

quiz Q4

connections at transport layer

unless we change transport layer
relies on being able to use network layer in same way

so need router-changing solution

quiz Q5

best scheme would be encrypt+auth with key 2 (not an option)

B allows confirming 'guesses' about message using MAC

C+D allow reading decrypted message

quiz Q6

best scheme would be encrypt+auth with key 2 (not an option)

B allows confirming 'guesses' about message using MAC

C+D allow reading decrypted message

anon feedback

"This course has the best TAs of any CS class I have taken so far, they help you with the actual implementation as well as making sure you fully understand the overarching concepts the homeworks and coursework are supposed to teach you. They're really doing a great job!"

"I have really enjoyed the labs in this course thus far. ...unlike all other labs so far, the openmp lab left me feeling frustrated and confused. The crux of the issue is the write-up's nebulous connection between the parallel mapping and reduction stages. Like, do you do them sequentially or together? I still don't know. I think a fully worked-out example showing..."

hoped that pseudocode under first reduce strategy would help...
providing worked out examples probably means more complex problem

exercise

suppose A, B have shared keys K_1, K_2

assume attackers do not have keys

E/D = encrypt/decrypt function

A asks B to pay Sue $100 by sending message with these parts:

"2023-11-03: pay $100"

$E(K_1, \text{“2023-11-03 Sue”})$

$MAC(K_2, \text{“2023-11-03 \$100”})$

1. can eavesdropper learn: (a) who is being paid, (b) how much?

2. can machine-in-middle change: (a) who is being paid, (b) how much?

shared secrets impractical

problem: shared secrets usually aren't practical

need secure communication before I can do secure communication?

scaling problems

- millions of websites $\times$ billions of browsers = how many keys?
- hard to talk to new people

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bootstrapping keys?

will still need to have some sort of secure communication to setup!

because we need some way to know we aren't talking to attacker

bootstrapping keys?

will still need to have some sort of secure communication to setup!

because we need some way to know we aren't talking to attacker

but...

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can be broadcast communication

- don't need full new sets of keys for each web browser

bootstrapping keys?

will still need to have some sort of secure communication to setup!

because we need some way to know we aren't talking to attacker

but...

can be broadcast communication

- don't need full new sets of keys for each web browser

only with smaller number of trusted authorities

- don't need to have keys for every website in advance

asymmetric encryption

we'll have two functions:

encrypt: $PE(\text{public key}, \text{message}) = \text{ciphertext}$
decrypt: $PD(\text{private key}, \text{ciphertext}) = \text{message}$

(public key, private key) = "key pair"

key pairs

‘private key’ = kept secret

- usually not shared with *anyone*

‘public key’ = safe to give to everyone

- usually some hard-to-reverse function of public key

concept will appear in some other cryptographic primitives

asymmetric encryption properties

functions:

encrypt: $PE(\text{public key}, \text{message}) = \text{ciphertext}$
decrypt: $PD(\text{private key}, \text{ciphertext}) = \text{message}$

should have:

knowing PE, PD, the public key, and ciphertext shouldn't make it too easy to find message
knowing PE, PD, the public key, ciphertext, and message shouldn't help in finding private key

secrecy properties with asymmetric

not going to be able to make things as hard as "try every possibly private key"

but going to make it impractical

like with symmetric encryption want to prevent recovery of *any info about message*

also have some other attacks to worry about:

e.g. no info about key should be revealed based on our reactions to decrypting maliciously chosen ciphertexts

using asymmetric v symmetric

both:

- use secret data to generate key(s)

asymmetric (AKA public-key) encryption

- one "keypair" per recipient
- private key kept by recipient
- public key sent to all potential senders
- encryption is one-way without private key

symmetric encryption

- one key per (recipient + sender)
- secret key kept by recipient + sender
- if you can encrypt, you can decrypt

using?

in advance: B generates private key + public key

in advance: B sends public key to A (and maybe others) securely

A computes PE(public key, 'The secret formula is...') = *******

send on network:
A $\rightarrow$ B: ********

B computes PD(private key, *******) = 'The secret formula is ...'

digital signatures

symmetric encryption : asymetric encryption ::
message authentication codes : digital signatures

digital signatures

pair of functions:

- sign: $S(\text{private key}, \text{message}) = \text{signature}$
- verify: $V(\text{public key}, \text{signature}, \text{message}) = 1$ ("yes, correct signature")

(public key, private key) = key pair (similar to asymmetric encryption)

- public key can be shared with everyone
- knowing S, V, public key, message, signature
- doesn't make it too easy to find another message + signature so that $V(\text{public key}, \text{other message}, \text{other signature}) = 1$

using?

in advance: A generates private key + public key

in advance: A sends public key to B (and maybe others) securely

A computes S(private key, 'Please pay ...') = *******

send on network:
A $\rightarrow$ B: 'Please pay ...', ********

B computes V(public key, 'Please pay ...', *******) = 1

tools, but...

have building blocks, but less than straightforward to use

lots of issues from using building blocks poorly

start of art solution: formal proof sytems

- mathematical proof that attacker doing X implies encryption/MAC/etc. broken
- ideally a somewhat machine-checkable proof

(we aren't going to be that formal...)

replay attacks

A→B: Did you order lunch? [signature 1 by A]

signature 1 by A = Sign(A's private signing key, "Did you order lunch?")
will check with Verify(A's public key, signature 1 by A, "Did you order lunch?")

B→A: Yes. [signature 1 by B]

signature 1 by B = Sign(B's private key, "Yes.")
will check with Verify(B's public key, signature 1 by B, "Yes.")

A→B: Vegetarian? [signature 2 by A]
B→A: No, not this time. [signature 2 by B]
...
A→B: There's a guy at the door, says he's here to repair the AC. Should I let him in? [signature N by A]

replay attacks

A→B: Did you order lunch? [signature 1 by A]
B→A: Yes. [signature 1 by B]
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...
A→B: There's a guy at the door, says he's here to repair the AC. Should I let him in? [signature ? by A]

how can attacker hijack the reponse to A's inquiry?

replay attacks

A→B: Did you order lunch? [signature 1 by A]
B→A: Yes. [signature 1 by B]
A→B: Vegetarian? [signature 2 by A]
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...
A→B: There's a guy at the door, says he's here to repair the AC. Should I let him in? [signature ? by A]

how can attacker hijack the reponse to A's inquiry?

as an attacker, I can copy/paste B's earlier message!

just keep the same signature, so it can be verified!

Verify(B's public key, "Yes.", signature 2 from B) = 1

nonces (1)

one solution to replay attacks:

A→B: #1 Did you order lunch? [signature 1 from A]
signature from A = Sign(A's private key, "#1 Did you order lunch?")

B→A: #1 Yes. [signature 1 from B]
A→B: #2 Vegetarian? [signature 2 from A]
B→A: #2 No, not this time. [signature 2 from B]
...
A→B: #54 There's a guy at the door, says he's here to repair the AC. Should I let him in? [signature ? from A]

(assuming A actually checks the numbers)

nonces (2)

another solution to replay attacks:

B→A: [next number #91523] [signature from B]
A→B: #91523 Did you order lunch? [next number #90382] [signature from A]
B→A: #90382 Yes. [next number #14578] [signature from B]
...
A→B: #6824 There's a guy at the door, says he's here to repair the AC. Should I let him in? [next number #36129][signature from A]

(assuming A actually checks the numbers)

replay attacks (alt)

M→B: #50 Did you order lunch? [signature by M]
B→M: #50 Yes. [signature intended for M by B]

A→B: #50 There's a guy at the door, says he's here to repair the AC. Should I let him in? [signature ? by A]

how can M hijack the reponse to A's inquiry?

replay attacks (alt)

M→B: #50 Did you order lunch? [signature by M]
B→M: #50 Yes. [signature intended for M by B]

A→B: #50 There's a guy at the door, says he's here to repair the AC. Should I let him in? [signature ? by A]

how can M hijack the reponse to A's inquiry?

as an attacker, I can copy/paste B's earlier message!

just keep the same signature, so it can be verified!

Verify(B's public key, "#50 Yes.", signature intended for M by B) = 1

confusion about who's sending?

in addition to nonces, either

- write down more who is sending + other context so message can't be reused and/or
- use unique set of keys for each principal you're talking to

with symmetric encryption, also "reflection attacks"

- A sends message to B, attacker sends A's message back to A as if it's from B

other attacks without breaking math

TLS state machine attack

from `https://mitls.org/pages/attacks/SMACK`

protocol:

step 1: verify server identity
step 2: receive messages from server

attack:

if server sends “here’s your next message”,
instead of “here’s my identity”
then broken client ignores verifying server’s identity

Matrix vulnerabilties

one example from `https://nebuchadnezzar-megolm.github.io/static/paper.pdf`

system for confidential multi-user chat

protocol + goals:

- each device (my phone, my desktop) has public key
- to talk to me, you verify one of my public keys
- to add devices, my client can forward my other devices' public keys

bug:

- when receiving new keys, clients did not check who they were forwarded from correctly

on the lab

getting public keys?

browser talking to websites
needs public keys of every single website?

not really feasible, but...

certificate idea

let's say A has B's public key already.

if C wants B's public key and knows A's already:

A can generate "certificate" for B:

> "B's public key is XXX" AND
> Sign(A's private key, "B's public key is XXX")

B send copy of their "certificate" to C (most common idea)

if C trusts A, now C has B's public key

> if C does not trust A, well, can't trust this either

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certificate authorities

websites (and others) go to *certificates authorities* (CA) with their public key

certificate authorities sign messages like:
"The public key for foo.com is XXX."

signed message called *certificate*

send certificates to browsers to verify identity

- website can forward certificate instead of browser contacting CA directly

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"The public key for foo.com is XXX."

signed message called *certificate*

send certificates to browsers to verify identity

website can forward certificate instead of browser contacting CA directly

example web certificate (1)

```
    Version: 3 (0x2)
    Serial Number: 7b:df:f6:ae:2e:d7:db:74:d3:c5:77:ac:bc:44:bf:1b
    Signature Algorithm: sha256WithRSAEncryption
    Issuer:
        countryName               = US
        stateOrProvinceName       = MI
        localityName              = Ann Arbor
        organizationName          = Internet2
        organizationalUnitName    = InCommon
        commonName                = InCommon RSA Server CA
    Validity
        Not Before: Apr 25 00:00:00 2023 GMT
        Not After : Apr 24 23:59:59 2024 GMT
    Subject:
        countryName               = US
        stateOrProvinceName       = Virginia
        organizationName          = University of Virginia
        commonName                = canvas.its.virginia.edu
....
    X509v3 extensions:
....
        X509v3 Subject Alternative Name: DNS:canvas.its.virginia.edu
```

example web certificate (2)

```
....
    Subject Public Key Info:
        Public Key Algorithm: rsaEncryption
            RSA Public-Key: (2048 bit)
            Modulus:
                00:a2:fb:5a:fb:2d:d2:a7:75:7e:eb:f4:e4:d4:6c:
                94:be:91:a8:6a:21:43:b2:d5:9a:48:b0:64:d9:f7:
                f1:88:fa:50:cf:d0:f3:3d:8b:cc:95:f6:46:4b:42:

....
Signature Algorithm: sha256WithRSAEncryption
Signature Value:
    24:3a:67:c8:0d:ef:eb:8c:eb:ba:8f:d5:11:d2:1e:ea:44:eb:
    fe:af:93:7d:d9:4a:2b:44:a3:7f:47:50:aa:d1:b3:9c:a8:a8:
....
```

certificate chains

That certificate signed by "InCommon RSA Server CA"

CA = certificate authority

so their public key, comes with my OS/browser?

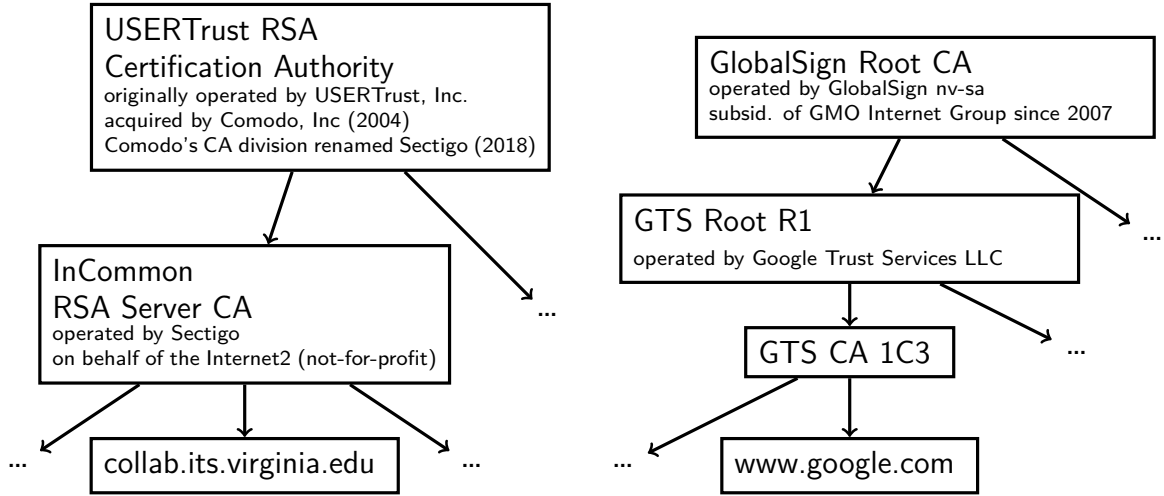
not exactly...

they have their own certificate signed by "USERTrust RSA Certification Authority"

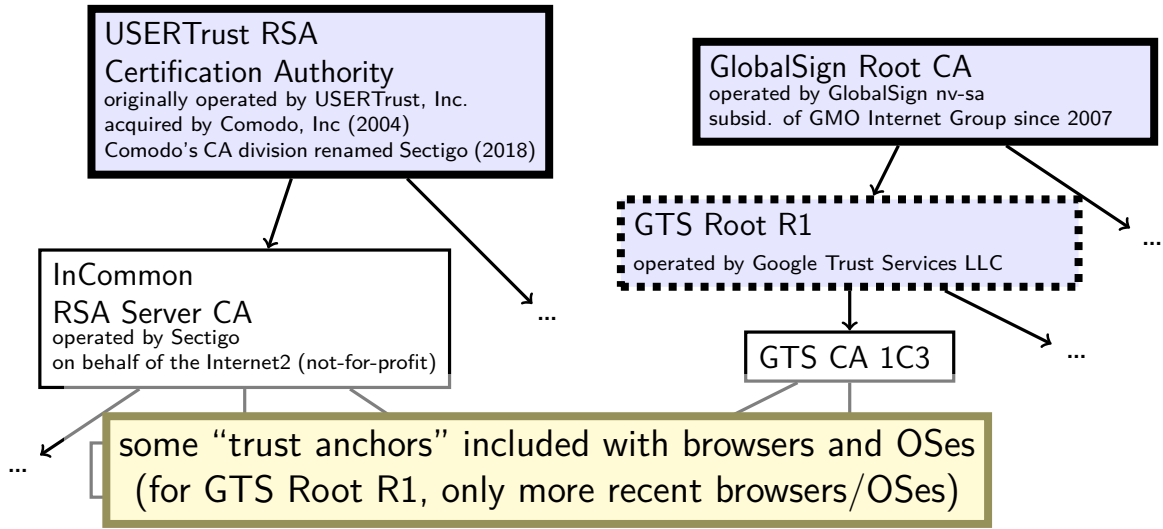
and their public key comes with your OS/browser?

(but both CAs now operated by UK-based Sectigo)

certificate hierarchy



certificate hierarchy



how many trust anchors?

Mozilla Firefox (as of 27 Feb 2023)

- 155 trust anchors
- operated by 55 distinct entities

Microsoft Windows (as of 27 Feb 2023)

- 237 trust anchors
- operated by 86 distinct entities

public-key infrastructure

ecosystem with certificate authorities
and certificates for everyone

called “public-key infrastructure”

several of these:

- for verifying identity of websites
- for verifying origin of domain name records (kind-of)
- for verifying origin of applications in some OSes/app stores/etc.
- for encrypted email in some organizations
- ...

exercise

exercise: how should website certificates verify identity?

how do certificate authorities verify

for web sites, set by CA/Browser Forum

organization of:

- everyone who ships code with list of valid certificate authorities
  - Apple, Google, Microsoft, Mozilla, Opera, Cisco, Qihoo 360, Brave, ...
- certificate authorities

decide on rules (“baseline requirements”) for what CAs do

BR domain name identity validation

options involve CA choosing random value and:

sending it to domain contact (with domain registrar) and receive response with it, or

observing it placed in DNS or website or sent from server in other specific way

exercise: problems this doesn't deal with?

some other things public CAs do

keep their private keys in tamper-resistant hardware

maintain publicly-accessible database of *revoked* certificates

- some browsers check these, sometimes

certificate transparency

- public logs of every certificate issued
- some browsers reject non-logged certificates
- so you can tell if bad certificate exists for your website

'CAA' records in the domain name system

- can indicate which CAs are allowed to issue certificates in DNS
- (but CAs apparently not required to use DNSSEC (certificate infrastructure for signing domain name records) when looking this up)

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backup slides

cryptographic hash uses

find shorter 'summary' to substitute for data

- what hashtables use them for, but...
- we care that adversaries can't cause collisions!

cryptographic hash uses

find shorter 'summary' to substitute for data

- what hashtables use them for, but...
- we care that adversaries can't cause collisions!

deal with message limits in signatures/etc.

password hashing — but be careful! [next slide]

constructing message authentication codes

- hash message + secret info (+ some other details)