



# secure communication context

“secure” communication

mostly talk about on network

between *principals*  $\approx$  people/servers/programs

but same ideas apply to, e.g., messages on disk  
communicating with yourself

# A to B

running example: A talking with B  
maybe sometimes also with C

attacker E — eavesdropper  
passive  
gets to read all messages over network

attacker M (man-in-the-middle)  
active  
gets to read and replace and add messages on the network

# privileged network position

intercept radio signal?

control local wifi router?

may doesn't just forward messages

compromise network equipment?

send packets with 'wrong' source address  
called "spoofing"

fool DNS servers to 'steal' name?

fool routers to send you other's data?

# possible security properties? (1)

what we'll talk about:

confidentiality — information shared only with those who should have it

authenticity — message genuinely comes from right principal (and not manipulated)

## possible security properties? (2)

important ones we won't talk about...:

repudiation — if A sends message to B, B can't prove to C it came from A

(takes extra effort to get along with authenticity)

forward-secrecy — if A compromised now, E can't use that to decode past conversations with B

anonymity — A can talk to B without B knowing who it is

...

# secrets

if A is talking to B are communicating,  
what stops M from pretending to be B?

assumption: B knows some **secret information** that M does not

# secrets

if A is talking to B are communicating,  
what stops M from pretending to be B?

assumption: B knows some **secret information** that M does not

start: assume A and B have a *shared secret* they both know  
(and M, E do not)

(later: easier to setup assumptions)



# bad ways to use shared secret

A  $\rightarrow$  B: What's the password?

B  $\rightarrow$  A: It's 'Abc\$xyM\$e'.

A  $\rightarrow$  B: That's right! Here's my confidential information.

# bad ways to use shared secret

A  $\rightarrow$  B: What's the password?

B  $\rightarrow$  A: It's 'Abc\$xyM\$e'.

A  $\rightarrow$  B: That's right! Here's my confidential information.

well, this doesn't really help:

- against E, who can read the password AND confidential info
- against M, who can also pretend to be A for B

# symmetric encryption

some magic math!

we'll be given two functions by expert:

encrypt:  $E(\text{key}, \text{message}) = \text{ciphertext}$

decrypt:  $D(\text{key}, \text{ciphertext}) = \text{message}$

key = shared secret

ideally small (easy to share) and chosen at random

unsolved problem: how to share it?

# symmetric encryption properties (1)

our functions:

encrypt:  $E(\text{key}, \text{message}) = \text{ciphertext}$

decrypt:  $D(\text{key}, \text{ciphertext}) = \text{message}$

knowing  $E$  and  $D$ , it should be hard to learn anything about the message from the ciphertext without key

“hard”  $\approx$  would have to try every possible key

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# secrecy properties

actually that's not secret enough, usually want to resist recovery of info about message or key even given...

partial info about the message, or

lots of other (message, ciphertext) pairs, or  
“known plaintext”

lots of (message, ciphertext) pairs for *other messages the attacker chooses*, or  
“chosen plaintext”

lots of (message, ciphertext) pairs encrypted under similar keys, or  
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# using?

in advance: A and B share encryption key

A computes  $E(\text{key}, \text{'The secret formula is...'}) = ***$

send on network:

A  $\rightarrow$  B: \*\*\*

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A  $\rightarrow$  B: \*\*\*

B computes  $D(\text{key}, ***) = \text{'The secret formula is ...'}$

# encryption is not enough

if B receives an encrypted message from A, and...

it makes sense when decrypted, why isn't that good enough?

problem: an active attacker M

can *selectively* manipulate the encrypted message

# manipulating encrypted data?

one example: common symmetric encryption approach:

- use random number + shared secret to...

- produce sequence of hard-to-guess bits  $x_i$  as long as the message

- produce ciphertext with xor:  $c_i = m_i \oplus x_i$

- message =  $m_0m_1m_2 \dots$ ; ciphertext = [random number] $c_0c_1c_2 \dots$

means that flipping  $c_i$  flips bit  $m_i$

also means that we can shorten messages silently

# manipulating messages

as an active attacker

if we know part of plaintext

can sometimes make it read anything else by flipping bits

“Pay \$100 to Bob” → “Pay \$999 to Bob”

we can shorten

“Pay \$100 to ABC Corp if they ...” → “Pay \$100 to ABC Corp”

we can corrupt selected parts of message and check the response is

e.g. what changes don't make B reject message as malformed?

# message authentication codes (MACs)

goal: use shared secret *key* to verify message origin

one function:  $MAC(\text{key}, \text{message}) = \text{tag}$

knowing  $MAC$  and the message and the tag, it should be hard to:

- find the value of  $MAC(\text{key}, \text{other message})$  — (“forge” the tag)

- find the key



## contrast: MAC v checksum

message authentication code acts like checksum, but...

checksum can be recomputed without any key

checksum meant to protect against accidents, not malicious attacks

checksum can be faster to compute + shorter

# using without encryption?

in advance: choose + share MAC key

A prepares message:

A computes 'Please pay \$100 to M.'

A computes  $MAC(\text{MAC key, 'Please pay \$100 to M.'}) = @@@$

A  $\rightarrow$  B: Please pay \$100 to M. @@@

# using without encryption?

in advance: choose + share MAC key

A prepares message:

A computes 'Please pay \$100 to M.'

A computes  $MAC(\text{MAC key, 'Please pay \$100 to M.'}) = @@@$

A  $\rightarrow$  B: Please pay \$100 to M. @@@

B processes message:

B recomputes  $MAC(\text{MAC key, 'Please pay \$100 to M.'})$

**rejects** if it doesn't match @@@

# using with encryption?

in advance: choose + share encryption key and MAC key

A prepares message:

A computes  $E(\text{encrypt key, 'The secret formula is...'}) = ***$

A computes  $MAC(\text{MAC key, ***}) = @@@$

A  $\rightarrow$  B: \*\*\* @@@

# using with encryption?

in advance: choose + share encryption key and MAC key

A prepares message:

A computes  $E(\text{encrypt key, 'The secret formula is...'}) = ***$

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A  $\rightarrow$  B: \*\*\* @@@

B processes message:

B recomputes  $MAC(\text{MAC key, ***})$

**rejects** if it doesn't match @@@

B computes  $D(\text{key, ***}) = \text{'The secret formula is ...'}$

# “authenticated encryption”

often encryption + MAC packaged together

name: authenticated encryption

# 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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## scaling problems

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

# 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

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can be broadcast communication

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

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because we need some way to know we aren't talking to attacker  
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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:  $PE(\text{public key, message}) = \text{ciphertext}$

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

$(\text{public key, private key}) = \text{"key pair"}$

# 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:  $PE(\text{public key, message}) = \text{ciphertext}$

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

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

# public keys

public key used to encrypt

can share this with everyone!

private key used to decrypt

kept secret

don't even share with people sending us messages

## using?

in advance: B generates private key + public key

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

A computes  $PE(\text{public key, 'The secret formula is...'}) = \text{*****}$

send on network:

A  $\rightarrow$  B: \*\*\*\*\*

B computes  $PD(\text{private key, *****}) = \text{'The secret formula is ...'}$

# digital signatures

symmetric encryption : asymmetric 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  $S(\text{private key}, \text{'Please pay ...'}) = \text{*****}$

send on network:

A  $\rightarrow$  B: 'I authorize the payment', \*\*\*\*\*

B computes  $V(\text{public key}, \text{'Please pay ...'}, \text{*****}) = 1$

## 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



# replay attacks

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

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

B→A: Yes. [signature 1 by B]

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

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 by A]

so attacker can't manipulate/forged messages, everything's okay?

## replay attacks

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

B→A: Yes. [signature 1 by B]

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

## replay attacks

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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]

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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 vulnerabilities

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 send C:

“B's public key is XXX” AND

Sign(A's private key, “B's public key is XXX”)

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

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

# certificate authorities

instead, have public keys of trusted *certificate authorities*  
only 10s of them, probably

websites go to certificates authorities with their public key

certificate authorities sign messages like:

“The public key for foo.com is XXX.”

these signed messages called “certificates”

# example web certificate (1)

Certificate:

Data:

Version: 3 (0x2)

Serial Number:

81:13:c9:49:90:8c:81:bf:94:35:22:cf:e0:25:20:33

Signature Algorithm: sha256WithRSAEncryption

Issuer:

commonName = InCommon RSA Server CA

organizationalUnitName = InCommon

organizationName = Internet2

localityName = Ann Arbor

stateOrProvinceName = MI

countryName = US

Validity

Not Before: Feb 28 00:00:00 2022 GMT

Not After : Feb 28 23:59:59 2023 GMT

Subject:

commonName = collab.its.virginia.edu

organizationalUnitName = Information Technology and Communication

organizationName = University of Virginia

stateOrProvinceName = Virginia

countryName = US

.....



# example web certificate (1)

Certificate:

Data:

....

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:

....

X509v3 extensions:

....

X509v3 Extended Key Usage:

TLS Web Server Authentication, TLS Web Client Authentication

....

X509v3 Subject Alternative Name:

DNS:collab.its.virginia.edu

DNS:collab-prod.its.virginia.edu

DNS:collab.itc.virginia.edu

Signature Algorithm: sha256WithRSAEncryption

39:70:70:77:2d:4d:0d:0a:6d:d5:d1:f5:0e:4c:e3:56:4e:31:

....

# certificate chains

That certificate signed by “InCommon RSA Server CA”

CA = certificate authority

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

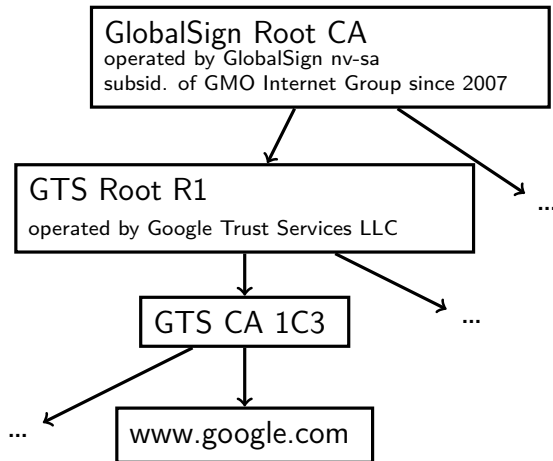
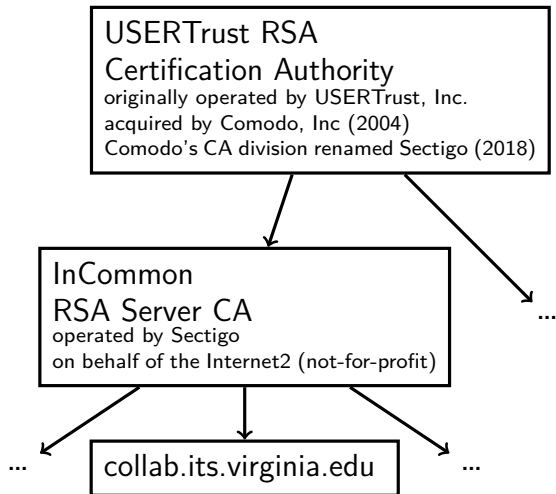
not exactly...

they have their own certificate signed by “USERTrust RSA Certification Authority”

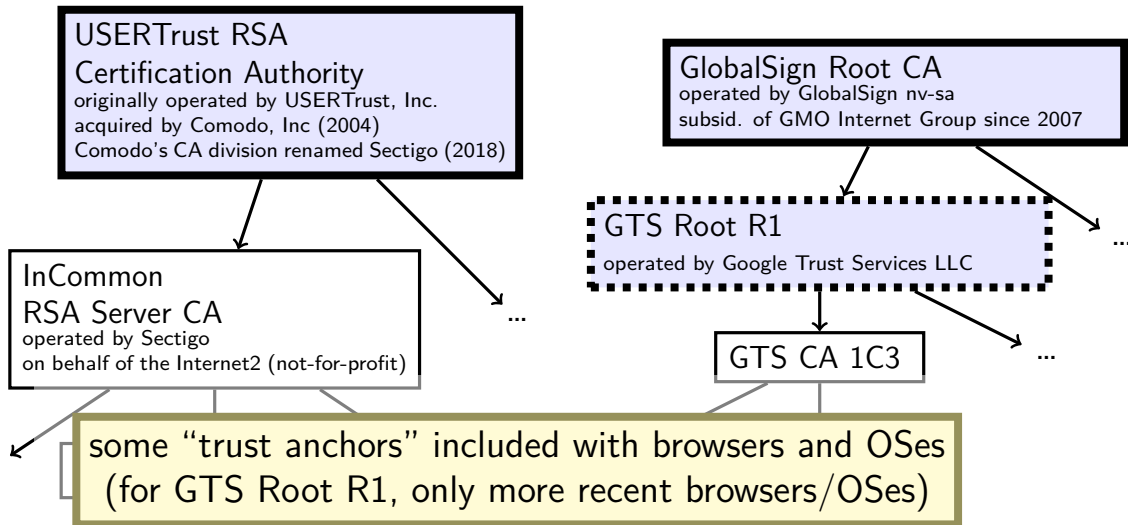
and their public key comes with your OS/browser?

(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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# motivation: summary for signature

mentioned that asymmetric encryption has size limit

same problem for digital signatures

solution: sign “summary” of message

how to get summary?

hash function, but...

# cryptographic hash

$$\text{hash}(M) = X$$

given  $X$ :

hard to find message other than by guessing

given  $X$ ,  $M$ :

hard to find second message so that  $\text{hash}(\text{second message}) = H$

# 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)

# password hashing

cryptographic hash functions are good at requiring guesses to 'reverse'

problem: guessing passwords is very fast

solution: slow/resource-intensive cryptographic hash functions

- Argon2i

- scrypt

- PBKDF2

# random numbers

need a lot of keys that no one else knows

common task: choose a *random* number

question: what does *random* mean here?

# cryptographically secure random numbers

security properties we might want for random numbers:

attacker cannot guess (part of) number better than chance

knowing prior 'random' numbers shouldn't help predict next 'random' numbers

compromising machine now shouldn't reveal older random numbers

**exercise: how to generate?**

# /dev/urandom

Linux kernel random number generator

collects “entropy” from hard-to-predict events

- e.g. exact timing of I/O interrupts

- e.g. some processor's built-in random number circuit

turned into as many random bytes as you want

# turning 'entropy' into random bytes

lots of ways to do this; one (rough/incomplete) idea:

internal variable *state*

to add 'entropy'

$\text{state} \leftarrow \text{SecureHash}(\text{state} + \text{entropy})$

to extract value:

$\text{random bytes} \leftarrow \text{SecureHash}(1 + \text{state})$

give bytes that can't be reversed to compute state

$\text{state} \leftarrow \text{SecureHash}(2 + \text{state})$

change state so attacker can't take us back to old state if compromised

# just asymmetric?

given public-key encryption + digital signatures...

why bother with the symmetric stuff?

symmetric stuff much faster

symmetric stuff much better at supporting larger messages



# key agreement

problem: A has B's public encryption key  
wants to choose shared secret

some ideas:

- A chooses a key, sends it encrypted to B

- A sends a public key encrypted B, B chooses a key and sends it back

# key agreement

problem: A has B's public encryption key  
wants to choose shared secret

some ideas:

- A chooses a key, sends it encrypted to B

- A sends a public key encrypted B, B chooses a key and sends it back

alternate model:

- both sides generate random values

- derive public-key like "key shares" from values

- use math to combine "key shares"

- kinda like A + B both sending each other public encryption keys

# Diffie-Hellman key agreement (2)

A and B want to agree on shared secret

A chooses random value  $Y$

A sends public value derived from  $Y$  (“key share”)

B chooses random value  $Z$

B sends public value derived from  $Z$  (“key share”)

A combines  $Y$  with public value from B to get number

B combines  $Z$  with public value from A to get number  
and b/c of math chosen, both get same number

# Diffie-Hellman key agreement (1)

math requirement:

some  $f$ , so  $f(f(X, Y), Z) = f(f(X, Z), Y)$   
(that's hard to invert, etc.)

choose  $X$  in advance and:

A randomly chooses $Y$	B randomly chooses $Z$
A sends $f(X, Y)$ to B	B sends $f(X, Z)$ to A
A computes $f(f(X, Z), Y)$	B computes $f(f(X, Y), Z)$

# key agreement and asym. encryption

can construct public-key encryption from key agreement

private key: generated random value  $Y$

public key: key share generated from that  $Y$

# key agreement and asym. encryption

can construct public-key encryption from key agreement

private key: generated random value  $Y$

public key: key share generated from that  $Y$

$PE(\text{public key, message}) =$

- generate random value  $Z$

- combine with public key to get shared secret

- use symmetric encryption + MAC using shared secret as keys

- output: (key share generated from  $Z$ ) (sym. encrypted data) (mac tag)

# key agreement and asym. encryption

can construct public-key encryption from key agreement

private key: generated random value  $Y$

public key: key share generated from that  $Y$

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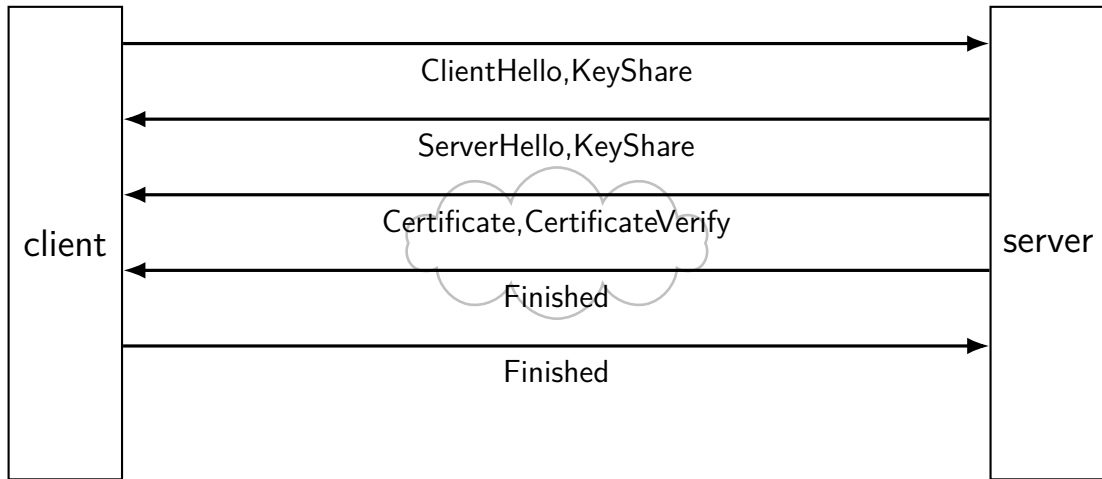
- output: (key share generated from  $Z$ ) (sym. encrypted data) (mac tag)

$PD(\text{private key, message}) =$

- extract (key share generated from  $Z$ )

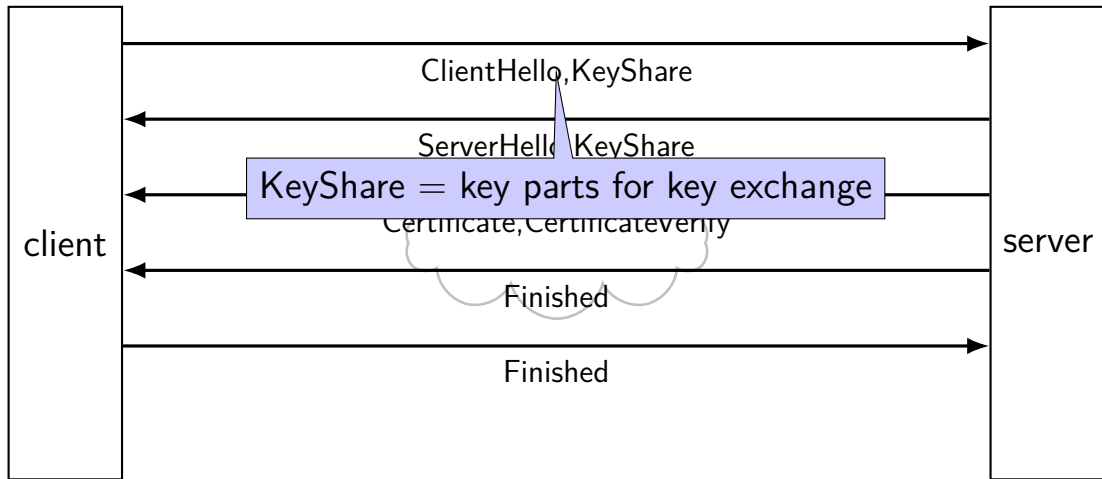
- combine with private key to get shared secret, ...

# typical TLS handshake

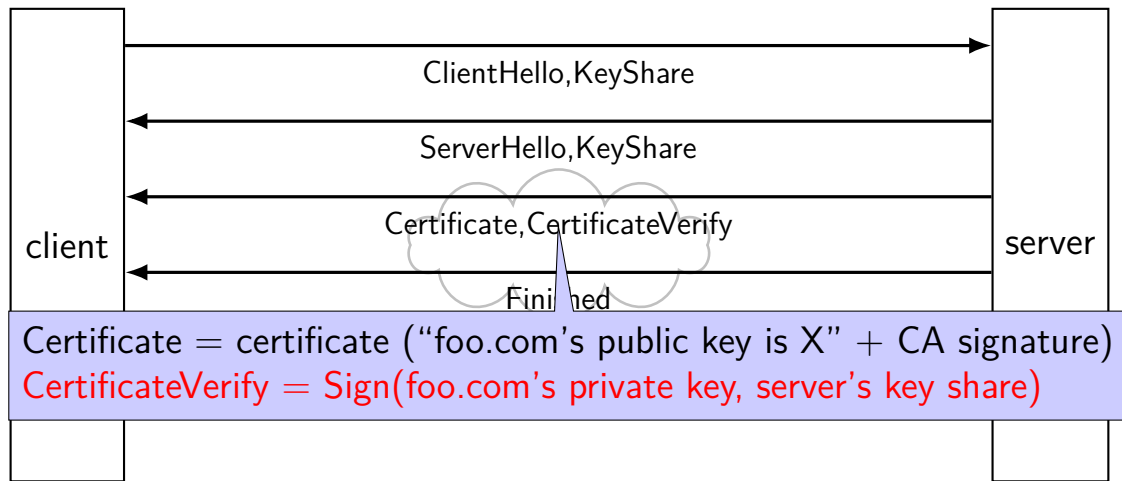




# typical TLS handshake



# typical TLS handshake



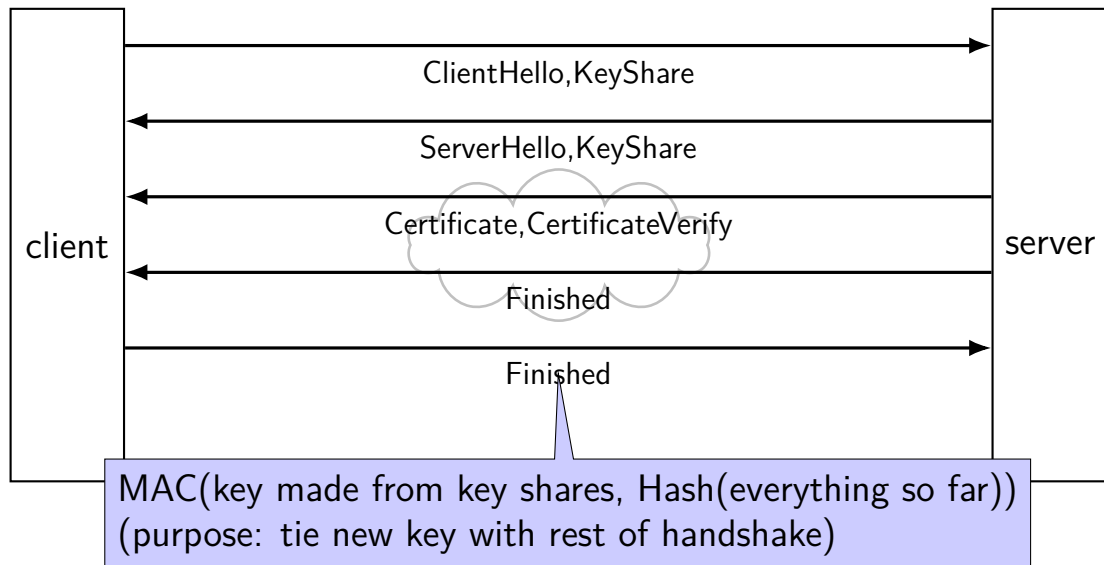
# typical TLS handshake



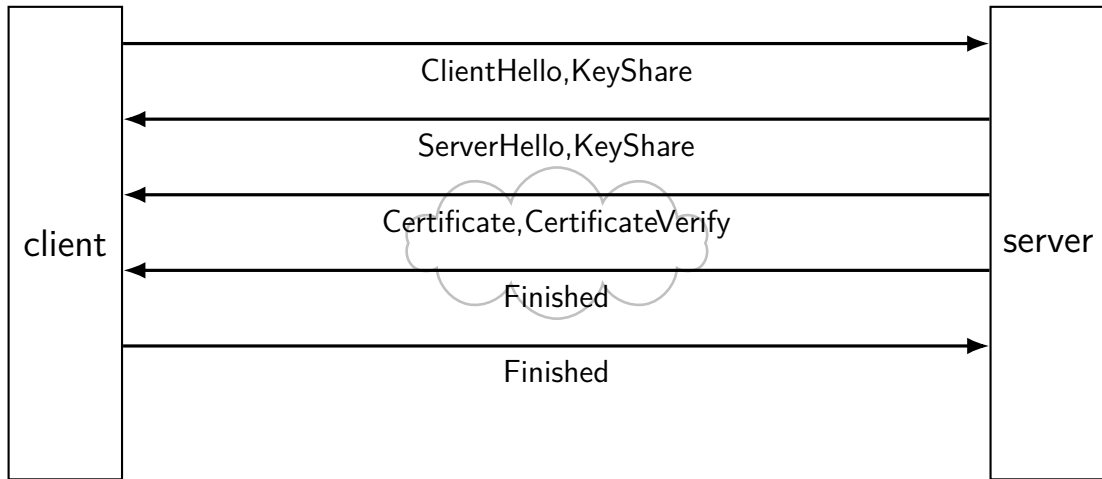
# typical TLS handshake



# typical TLS handshake



# typical TLS handshake



# TLS: after handshake

use key shares results to get **several** keys

take  $\text{hash}(\text{something} + \text{shared secret})$  to derive each key

separate keys for each direction (server  $\rightarrow$  client and vice-versa)

often separate keys for encryption and MAC

later messages use encryption + MAC + nonces

# things modern TLS usually does

(not all these properties provided by all TLS versions and modes)

confidentiality/authenticity

- server = one ID'd by certificate

- client = same throughout whole connection

forward secrecy

- can't decrypt old conversations (data for KeyShares is temporary)

fast

- most communication done with more efficient symmetric ciphers

- 1 set of messages back and forth to setup connection



# denial of service (1)

so far: worried about network attacker disrupting confidentiality/authenticity

what if we're just worried about just breaking things

well, if they control network, nothing we can do...

but often worried about less

## denial of service (2)

if you just want to inconvenience...

attacker just sends lots of stuff to my server

my server becomes overloaded?

my network becomes overloaded?

but: doesn't this require a lot of work for attacker?

exercise: why is this often not a big obstacle

# denial of service: asymmetry

work for attacker  $>$  work for defender

how much computation per message?

- complex search query?

- something that needs tons of memory?

- something that needs to read tons from disk?

how much sent back per message?

resources for attacker  $>$  resources of defender

how many machines can attacker use?

# denial of service: reflection/amplification

instead of sending messages directly...attacker can send messages  
“from” you to third-party

third-party sends back replies that overwhelm network

example: short DNS query with lots of things in response

“amplification” =

third-party inadvertently turns small attack into big one

# firewalls

don't want to expose network service to everyone?

solutions:

- service picky about who it accepts connections from
- filters in OS on machine with services
- filters on router

later two called “firewalls”

# firewall rules examples?

ALLOW tcp port 443 (https) FROM everyone

ALLOW tcp port 22 (ssh) FROM my desktop's IP address

BLOCK tcp port 22 (ssh) FROM everyone else

ALLOW from address X to address Y

...

# network security summary (1)

communicating securely with math

- secret value (shared key, public key) that attacker can't have

- symmetric: shared keys used for ed/encryption + auth/verify; fast

- asymmetric: public key used by any for encrypt + verify; slower

- asymmetric: private key used by holder for decrypt + sign; slower

protocol attacks — repurposing encrypt/signed/etc. messages

certificates — verifiable forwarded public keys

key agreement — for generated shared-secret “in public”

- publish key shares from private data

- combine private data with key share for shared secret

## network security summary (2)

TLS: combine all cryptography stuff to make “secure channel”

denial-of-service — attacker just disrupts/overloads (not subtle)

firewalls



**backup slides**