network address translation

IPv4 addresses are kinda scarce

solution: *convert* many private addrs. to one public addr.

locally: use private IP addresses for machines

outside: private IP addresses become a single public one

commonly how home networks work (and some ISPs)

implementing NAT

remote host + port	outside local port number	inside IP	inside port number
128.148.17.3:443	54033	192.168.1.5	43222
11.7.17.3:443	53037	192.168.1.5	33212
128.148.31.2:22	54032	192.168.1.37	43010
128.148.17.3:443	63039	192.168.1.37	32132

table of the translations

need to update as new connections made

NAT and layers

previously: network layer responsible for get to right machine

now: network + transport layer

- because we use port numbers

also, NAT needs to know about connections (transport layer)

- to know how to setup/remove table entries

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 chosen at random
- should be small — otherwise impractical to share
- unsolved problem: how do A and B both know this?

symmetric encryption properties

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 about the message from the ciphertext without key; or
learn about the key from the ciphertext and message

"hard" $\approx$ would have to try every possible key

using?

in advance: share secret key

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

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

B computes D(key, ***) = '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 $= m_0 m_1 m_2 \ldots$; ciphertext $=$ [random number]$c_0 c_1 c_2 \ldots$

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 make it read anything else by flipping bits

- "Pay $100 to Bob" $\rightarrow$ "Pay $999 to Bob"

we can shorten

- "Pay $100 to ABC Corp if they ..." $\rightarrow$ "Pay $100 to ABC Corp"

we can corrupt and what 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 $MAC(\text{key}, \text{other message})$
  - "forging 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?

in advance: choose + share encryption key and MAC key

A prepares message:

A computes E(encrypt key, 'The secret formula is...') = ***

A computes MAC(MAC key, ***) = @@@

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

B processes message:

B recomputes MAC(MAC key, ***)

rejects if it doesn't match @@@

B computes D(key, ***) = '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?

need to redo it every time I talk to new person?

scaling problem: millions of websites $\times$ billions of browsers $=$ how many keys?

shared secrets impractical

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need secure communication before I can do secure communication?

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scaling problem: millions of websites $\times$ billions of browsers $=$ how many keys?

bootstrapping keys?

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

but will minimize:

bootstrapping keys?

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

but will minimize:

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

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but will minimize:

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"

generated together
public key can be shared with everyone
private key = unshared secret!
knowing PE, PD, the public key, and ciphertext shouldn't make it too easy to find message
(or the private key)

asymmetric encryption

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encrypt: $PE(\text{public key}, \text{message}) = \text{ciphertext}$
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knowing PE, PD, the public key, and ciphertext shouldn't make it too easy to find message
(or the private key)

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(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: 'I authorize the payment', ********

B computes V(private 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

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 by A]

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

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]
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]

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]
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]

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 send C:

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

exercise

exercise: how should 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 identity validation

options involve CA choosing random value and:

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

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

exercise: problems this doesn't deal with?

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

hash(M) = X

given X:

hard to find message other than by guessing

given X, M:

hard to find second message so that hash(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

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

alternate model:

- use public-key encryption like 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 B to get number

and b/c of math chosen, both get same number

Diffie-Hellman key agreement (1)

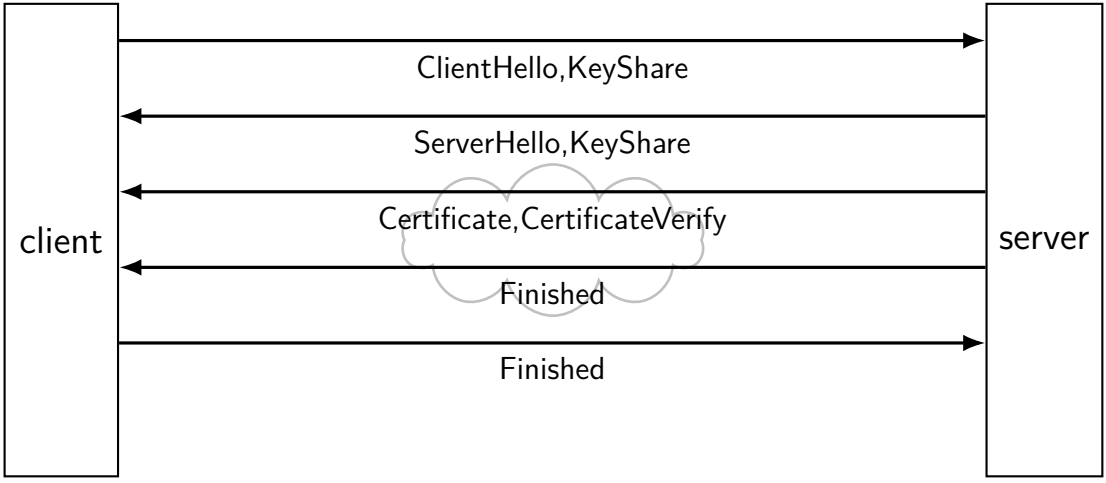
math requirement:

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

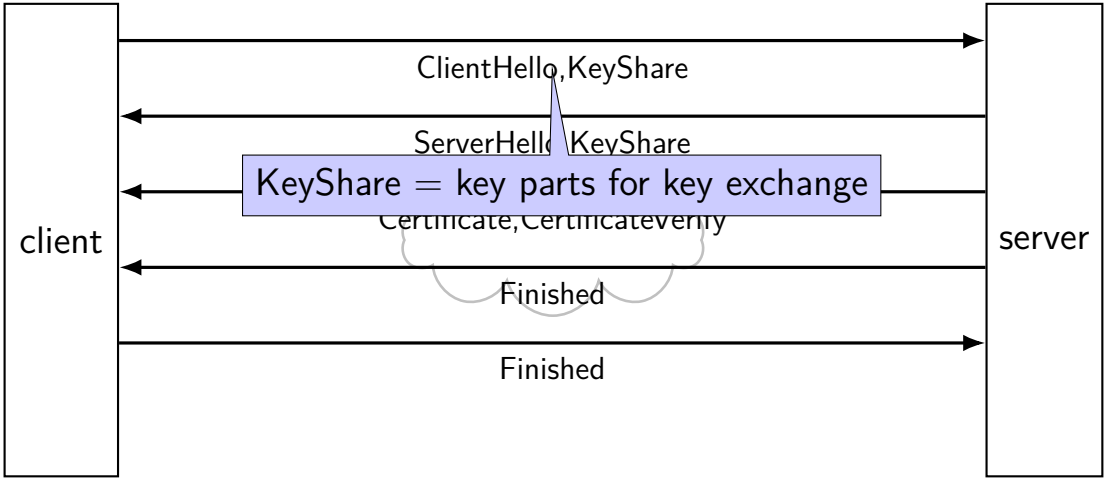
choose X in advance and:

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 $f(f(X,Y),Z)$

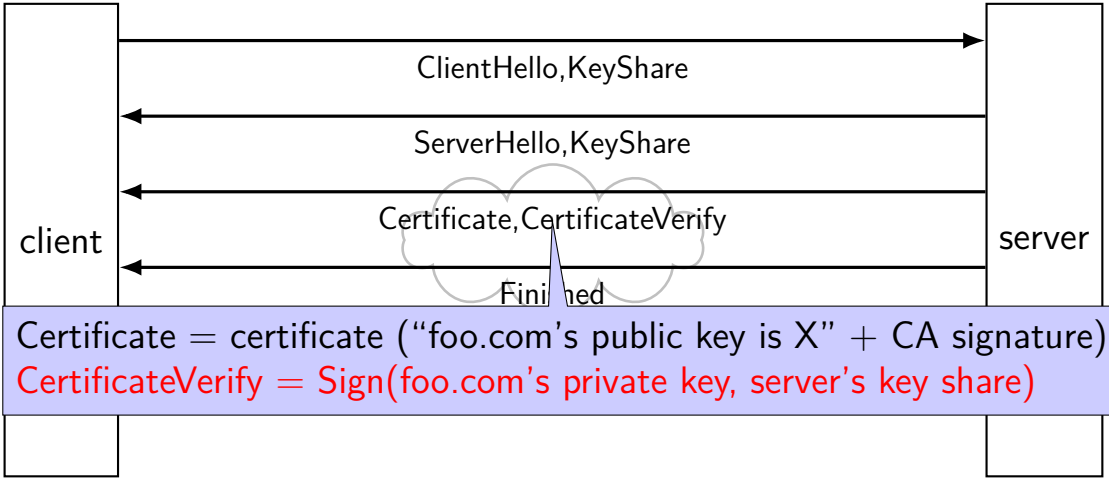
typical TLS handshake



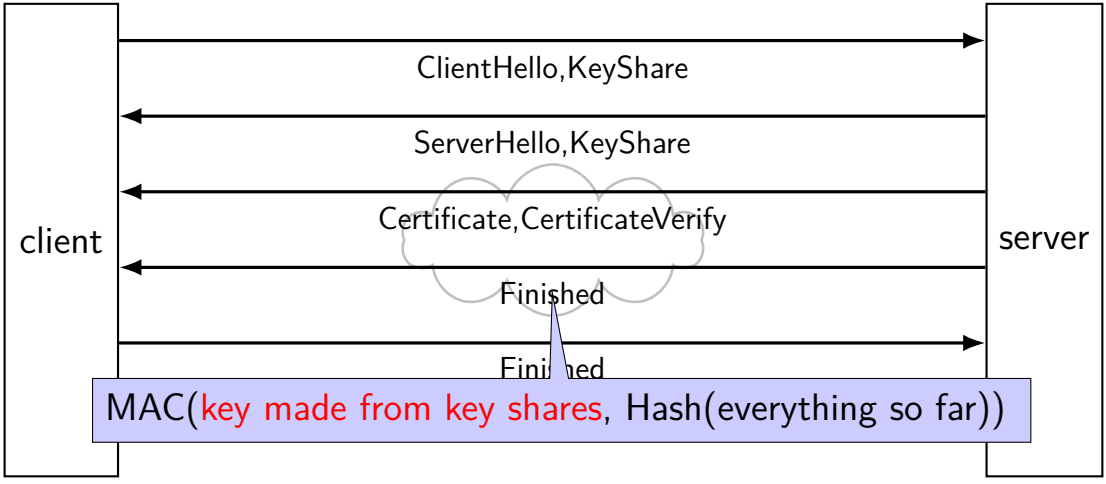
typical TLS handshake



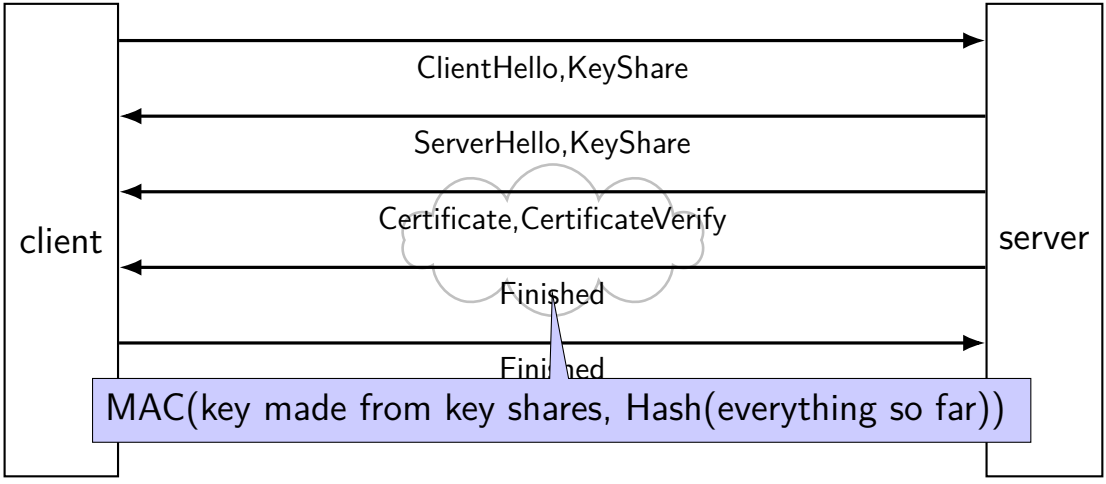
typical TLS handshake



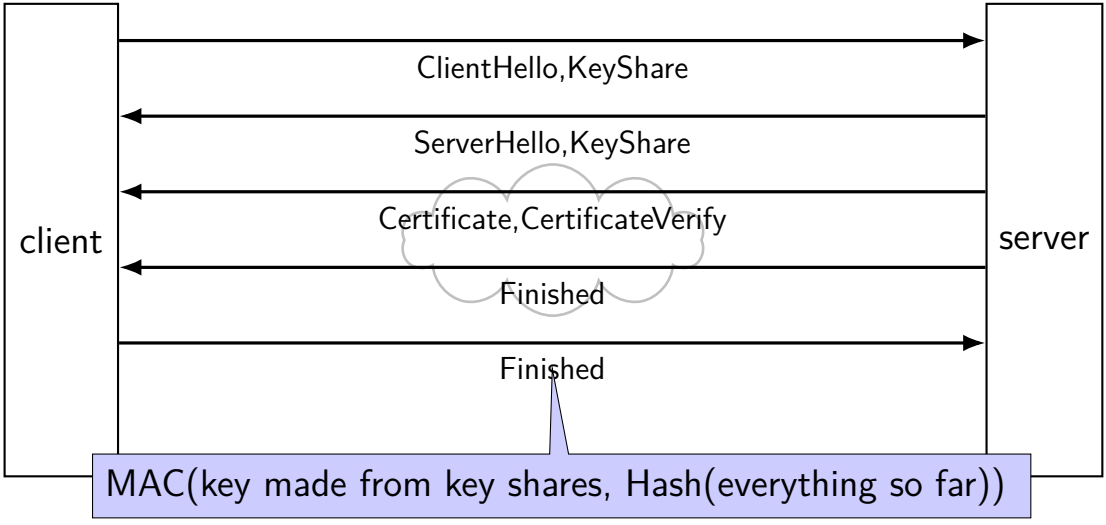
typical TLS handshake



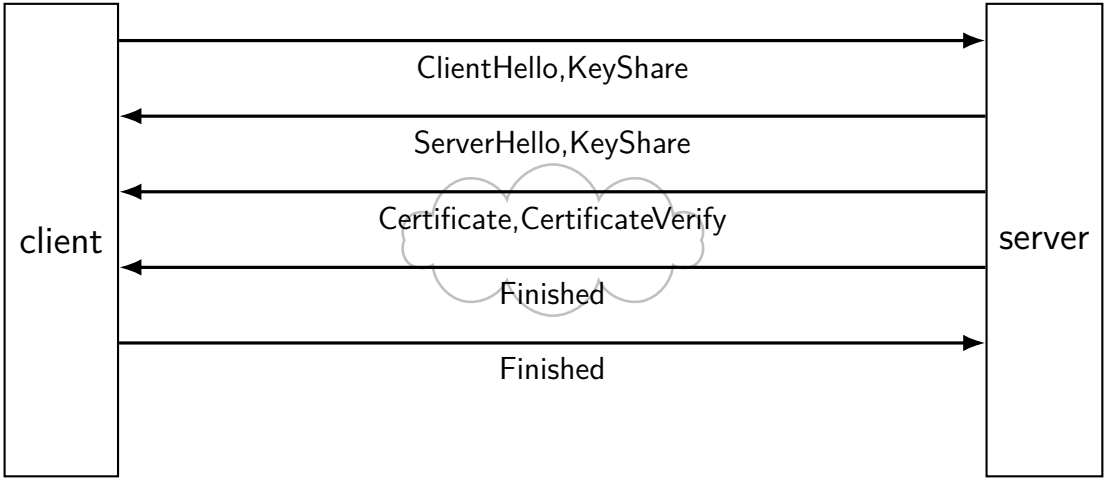
typical TLS handshake



typical TLS handshake



typical TLS handshake



TLS: after handshake

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

take hash(something + 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

denial of service

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 inadvertantly 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

...

backup slides

backup slides