putting it all together (1)

1. connect to local wifi network

2. open http://foo.com/bar in web browser

putting it all together (1)

1. connect to local wifi network
   a. ask local network for configuration — DHCP
   a. find out MAC addresses on local network
2. open http://foo.com/bar in web browser

putting it all together (1)

1. connect to local wifi network
    a. ask local network for configuration — DHCP
    a. find out MAC addresses on local network

2. open http://foo.com/bar in web browser
    a. lookup foo.com — DNS
    b. start connection to foo.com + correct port
    c. translate URL into HTTP message + read response

putting it all together (2)

1. connect to local wifi network
    a. ask local network for configuration

putting it all together (2)

1. connect to local wifi network
    a. ask local network for configuration

(DHCP) us -> all on local network: give me an address

(DHCP) local router -> us: use the following:

your IP	192.0.2.43
local network	192.0.2.0 through 192.0.2.255
gateway to other networks	192.0.2.1
DNS server	198.51.100.34
valid for	8 hours (ask later to renew)

putting it all together (3)

1. connect to local wifi network
    b. find out MAC addresses on local network

putting it all together (3)

1. connect to local wifi network
    b. find out MAC addresses on local network

us -> all local: who has 192.0.2.1 (geteway's IP address)?

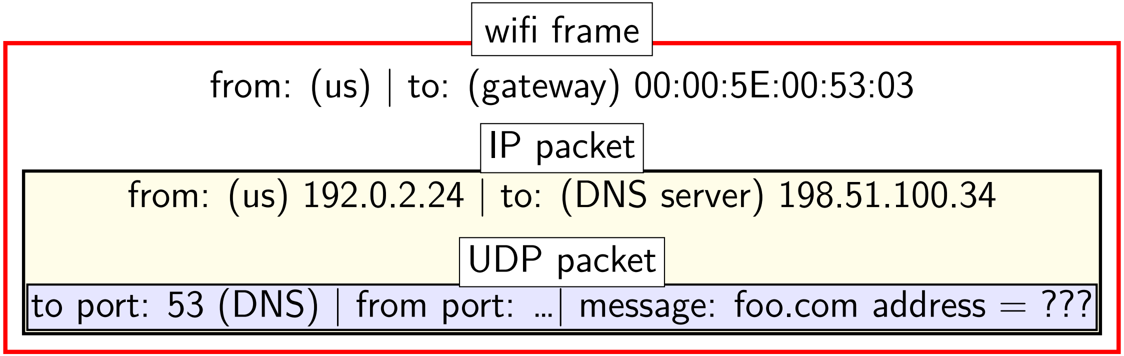
gateway -> us: I am 192.0.2.1, my MAC address is 00:00:5E:00:53:03

putting it all together (4a)

2. open http://foo.com/bar in web browser
   a. lookup foo.com

putting it all together (4a)

2. open http://foo.com/bar in web browser
    a. lookup foo.com



wifi frame

from: (us) | to: (gateway) 00:00:5E:00:53:03

IP packet

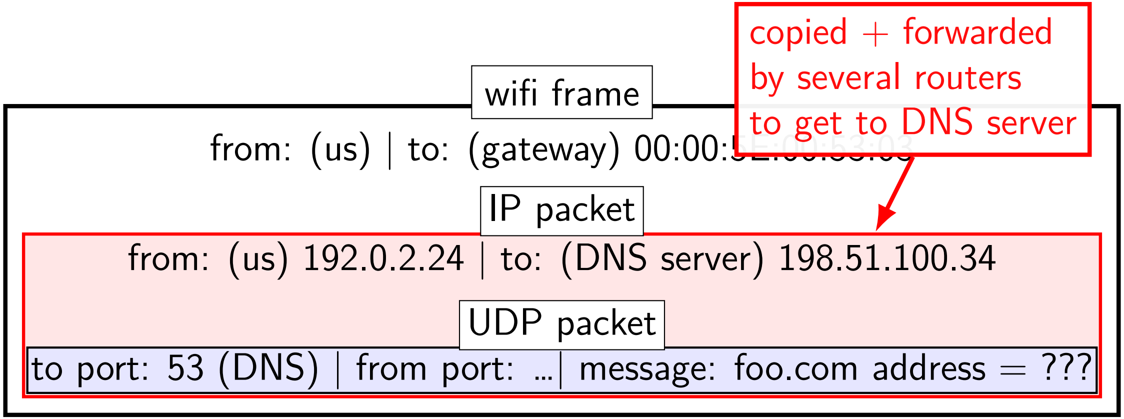
from: (us) 192.0.2.24 | to: (DNS server) 198.51.100.34

UDP packet

to port: 53 (DNS) | from port: ...| message: foo.com address = ???

putting it all together (4a)

2. open http://foo.com/bar in web browser
   a. lookup foo.com


copied + forwarded by several routers to get to DNS server
wifi frame
from: (us) | to: (gateway) 00:00:5E:00:53:03
IP packet
from: (us) 192.0.2.24 | to: (DNS server) 198.51.100.34
UDP packet
to port: 53 (DNS) | from port: ... | message: foo.com address = ???

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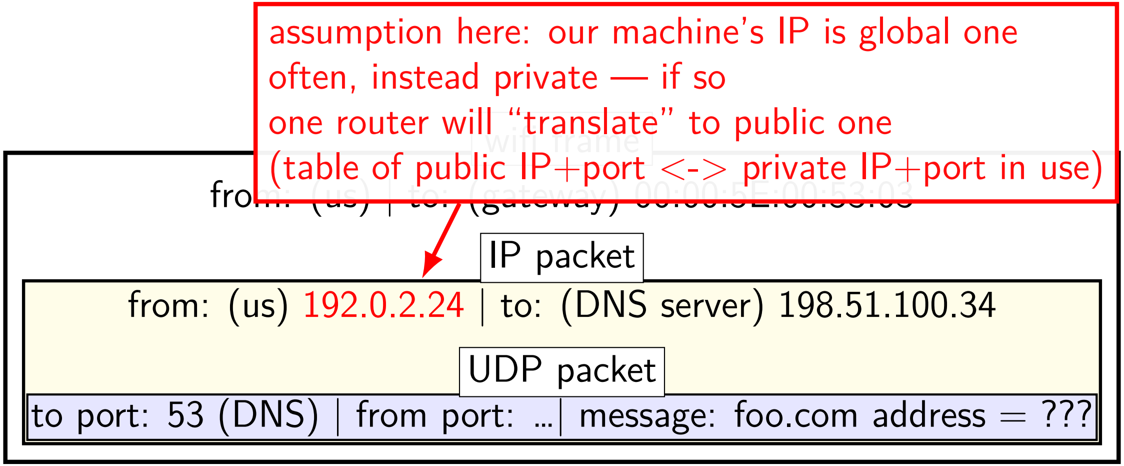

assumption here: our machine's IP is global one
often, instead private — if so
one router will "translate" to public one
(table of public IP+port <-> private IP+port in use)
wifi frame
from: (us) | to: (gateway) 00:00:5E:00:53:03
IP packet
from: (us) 192.0.2.24 | to: (DNS server) 198.51.100.34
UDP packet
to port: 53 (DNS) | from port: ... | message: foo.com address = ???

putting it all together (4c)

2. open http://foo.com/bar in web browser
   a. lookup foo.com

ISP's DNS server receives request

either sends back cached response (if recent, valid one)

or looks up in hierarchy of DNS servers

    ISP server -> root server: who is foo.com
    root server -> ISP server: try .com servers at 200.4.3.2
    ISP server -> .com servers: ...
    ...

putting it all together (4c)

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   a. lookup foo.com

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  ISP server -> root server: who is foo.com
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putting it all together (5)

2. open http://foo.com/bar in web browser
    b. start connection to foo.com + correct port

putting it all together (5)

2. open http://foo.com/bar in web browser
    b. start connection to foo.com + correct port

web browser creates socket, asks to connect to foo.com

In OS:

source port	destination IP	dest port	program/pid/fd
...	...	...	...
(OS assigned)	203.0.113.44 (foo.com)	80 (http)	browser/705/41
...	...	...	...

OS sends message (via multiple routers) to start connection

putting it all together (6)

2. open http://foo.com/bar in web browser
    c. translate URL to HTTP message + read response

putting it all together (6)

2. open http://foo.com/bar in web browser
   c. translate URL to HTTP message + read response

browser: `write(fd, "GET /bar HTTP/1.1…", …)`

browser: read response

message is split into multiple chunks
    (and forwarded through gateway)

acknowledgments, resending, etc. done by OSes at both ends

last time (1)

autoconfiguration (DHCP)
- ask on local network for configuration

IP to MAC address mapping (ARP / ND)
- network configuration indicates which IPs are local
- identifies “gateway” to non-local networks
- ask everyone on local network: what MAC address for this IP?

DNS (domain name system)
- ISP has server that does multi-step lookup + caches result
- cache has timeout

network address translation
- special router maps (many IP+ports) to (one IP+ports)

last time: secure channels

defending against eavesdropping/machine-in-middle

use *shared secret* = shared key(s)

- need to be shared securely in advance somehow (seems hard!)

encryption: E(key, plaintext) = ciphertext; D(key, ciphertext) = plaintext

- for confidentiality: ciphertext encodes plaintext message, but…
- ciphertext is useless without the key
- input called plaintext; output called ciphertext

message authentication codes: MAC(key, message) = tag

- "keyed checksum/hash" sometimes called a "tag"
- for authenticity: can use it verify message wasn't tampered with

last time: secure channels

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- "keyed checksum/hash" sometimes called a "tag"
- for authenticity: can use it verify message wasn't tampered with

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”
$E(K_1,$ “2023-11-03 Sue”$)$
$MAC(K_2,$ “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

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

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

replay attacks

A$\rightarrow$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$\rightarrow$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$\rightarrow$B: Vegetarian? [signature 2 by A]
B$\rightarrow$A: No, not this time. [signature 2 by B]
...
A$\rightarrow$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]

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$\rightarrow$B: Did you order lunch? [signature 1 by A]
B$\rightarrow$A: Yes. [signature 1 by B]
A$\rightarrow$B: Vegetarian? [signature 2 by A]
B$\rightarrow$A: No, not this time. [signature 2 by B]
...
A$\rightarrow$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$\rightarrow$B: #50 Did you order lunch? [signature by M]
B$\rightarrow$M: #50 Yes. [signature intended for M by B]

A$\rightarrow$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(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?

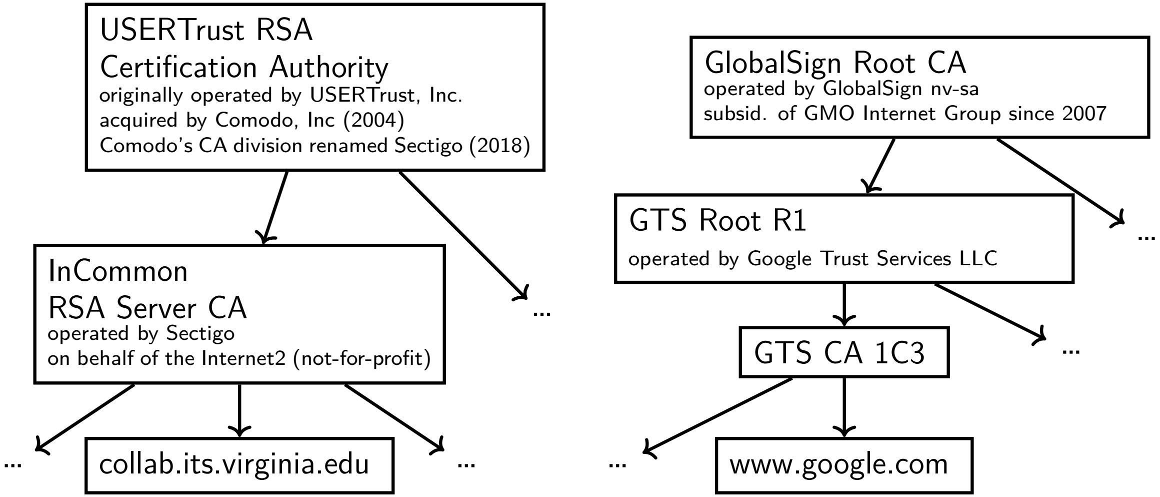
not exactly...

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

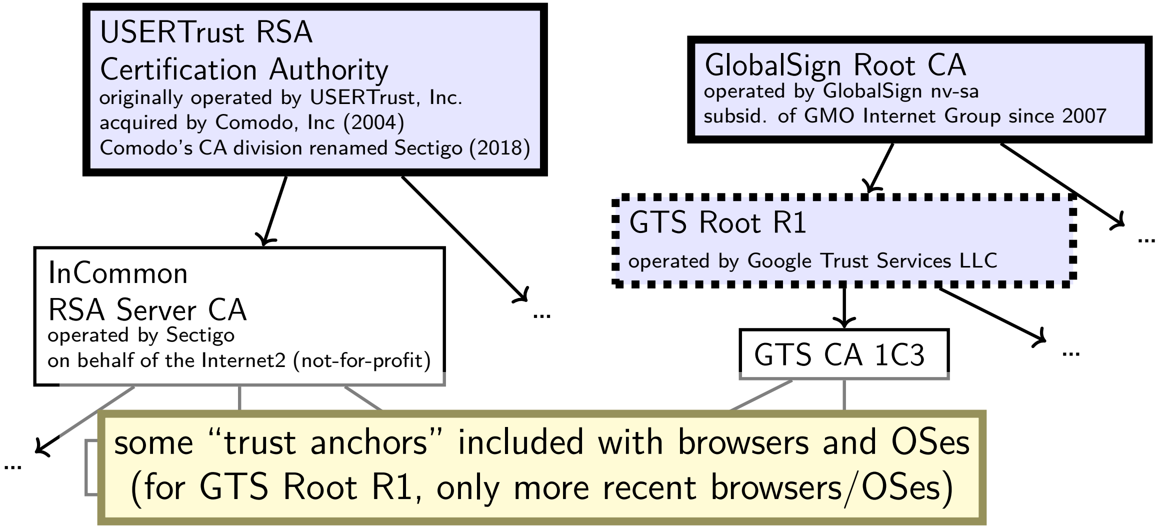
and their public key comes with your OS/browser?

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

certificate hierarchy


USERTrust RSA Certification Authority
originally operated by USERTrust, Inc.
acquired by Comodo, Inc (2004)
Comodo's CA division renamed Sectigo (2018)
InCommon RSA Server CA
operated by Sectigo
on behalf of the Internet2 (not-for-profit)
collab.its.virginia.edu
...
GlobalSign Root CA
operated by GlobalSign nv-sa
subsid. of GMO Internet Group since 2007
GTS Root R1
operated by Google Trust Services LLC
GTS CA 1C3
www.google.com
...

certificate hierarchy



USERTrust RSA Certification Authority
originally operated by USERTrust, Inc.
acquired by Comodo, Inc (2004)
Comodo's CA division renamed Sectigo (2018)
InCommon RSA Server CA
operated by Sectigo
on behalf of the Internet2 (not-for-profit)
GlobalSign Root CA
operated by GlobalSign nv-sa
subsid. of GMO Internet Group since 2007
GTS Root R1
operated by Google Trust Services LLC
GTS CA 1C3
…
…
…
…

some "trust anchors" included with browsers and OSes
(for GTS Root R1, only more recent browsers/OSes)

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

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’

idea: store cryptographic hash of password instead of password

- attacker who gets hash doesn’t get password
- can still check entered password is correct

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problem: with fast hash function, can try lots of guesses fast

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solution: special 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’

state $\leftarrow$ SecureHash(state + entropy)

to extract value:

random bytes $\leftarrow$ SecureHash(1 + state)
give bytes that can’t be reversed to compute state

state $\leftarrow$ SecureHash(2 + 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 agreeement

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 agreeement

private key: generated random value Y

public key: key share generated from that Y

PE(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 agreeement

private key: generated random value Y

public key: key share generated from that Y

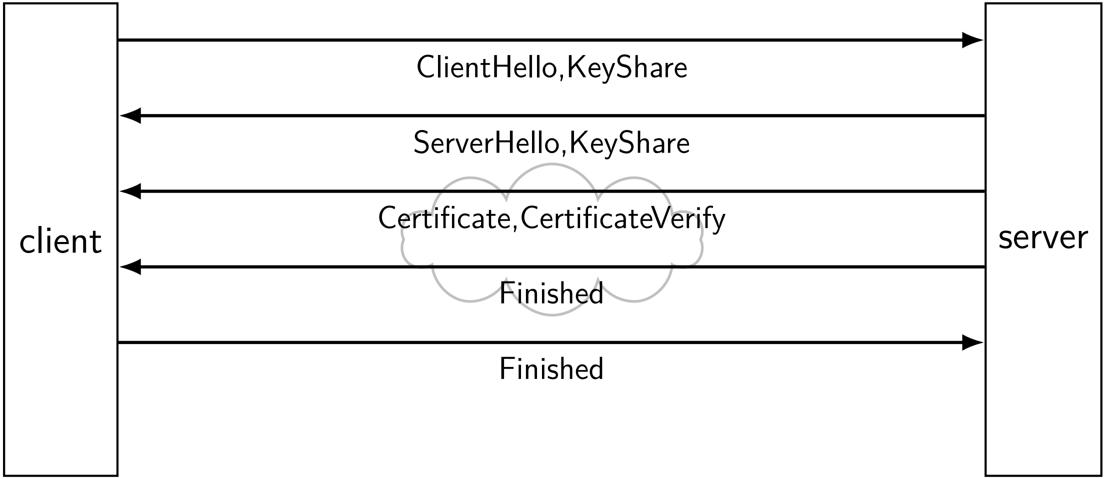
PE(public key, message) =

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)

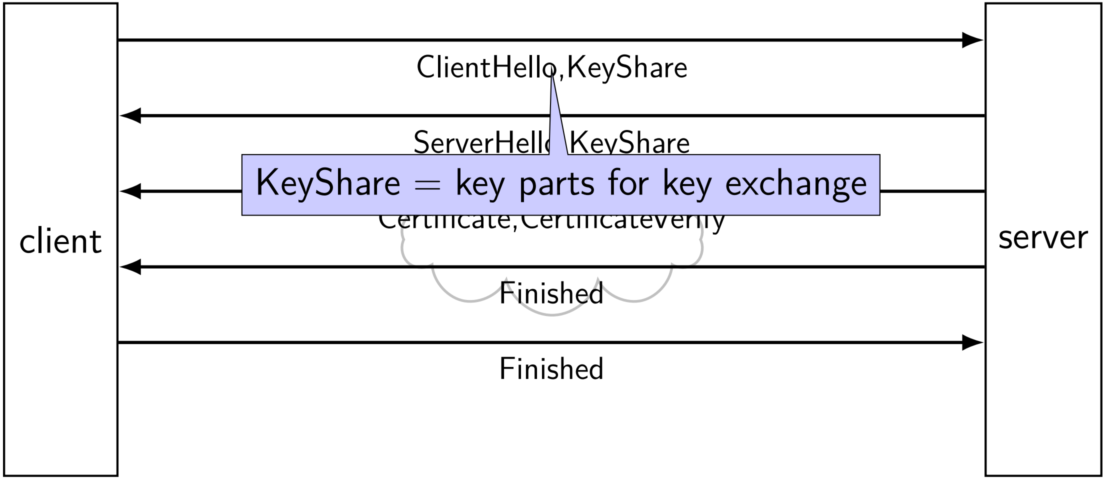
PD(private key, message) =

extract (key share generated from Z)
combine with private key to get shared secret, ...

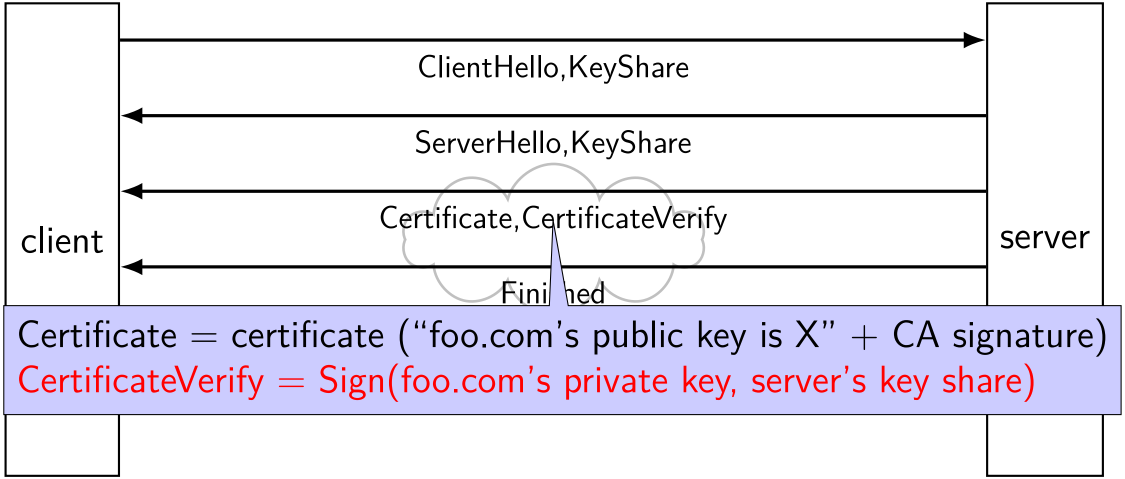
typical TLS handshake



typical TLS handshake



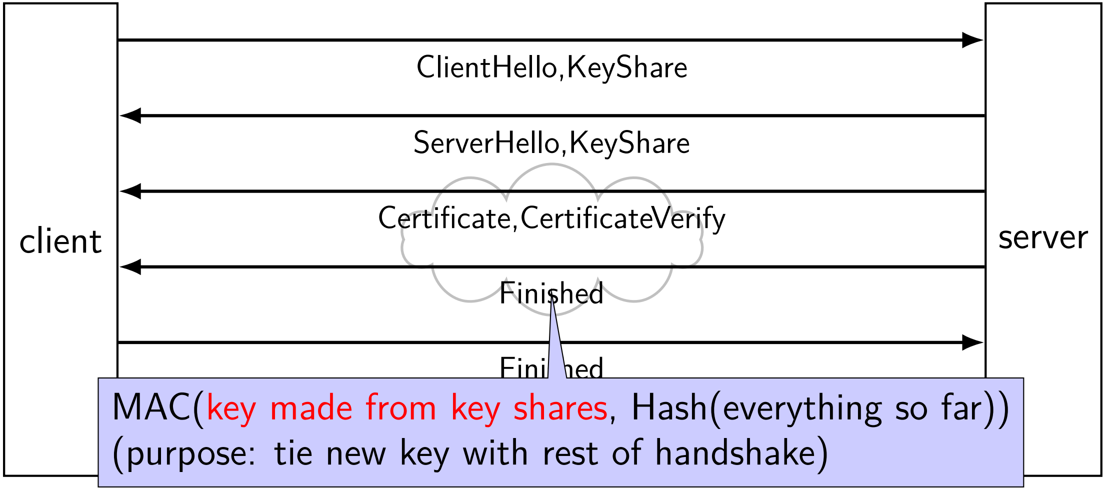
typical TLS handshake



Certificate = certificate (“foo.com’s public key is X” + CA signature)

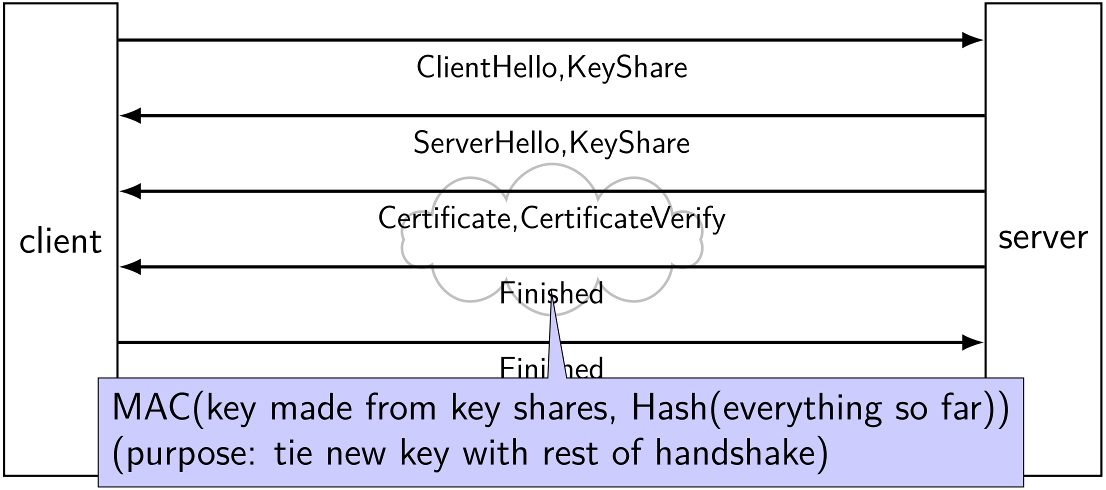
CertificateVerify = Sign(foo.com’s private key, server’s key share)

typical TLS handshake



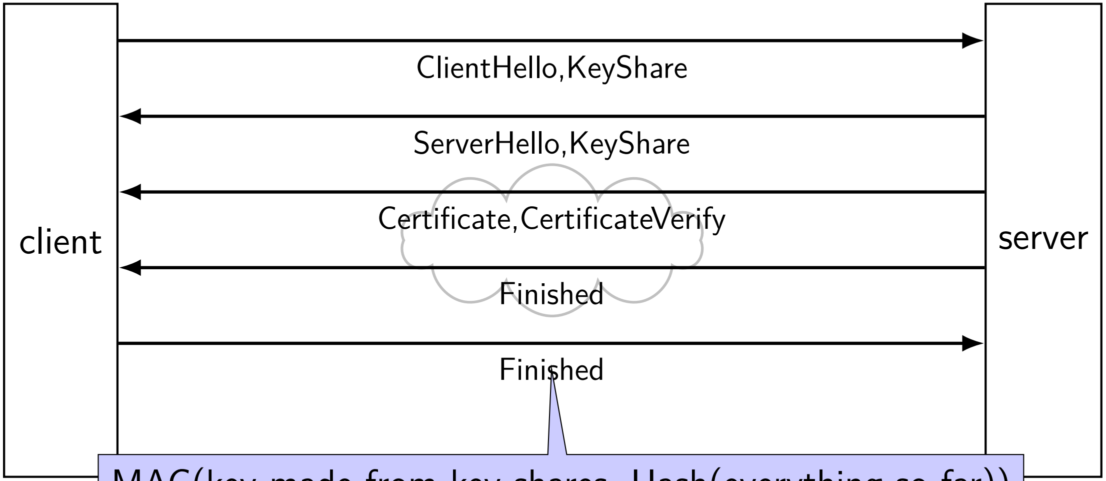
MAC(key made from key shares, Hash(everything so far))
(purpose: tie new key with rest of handshake)

typical TLS handshake



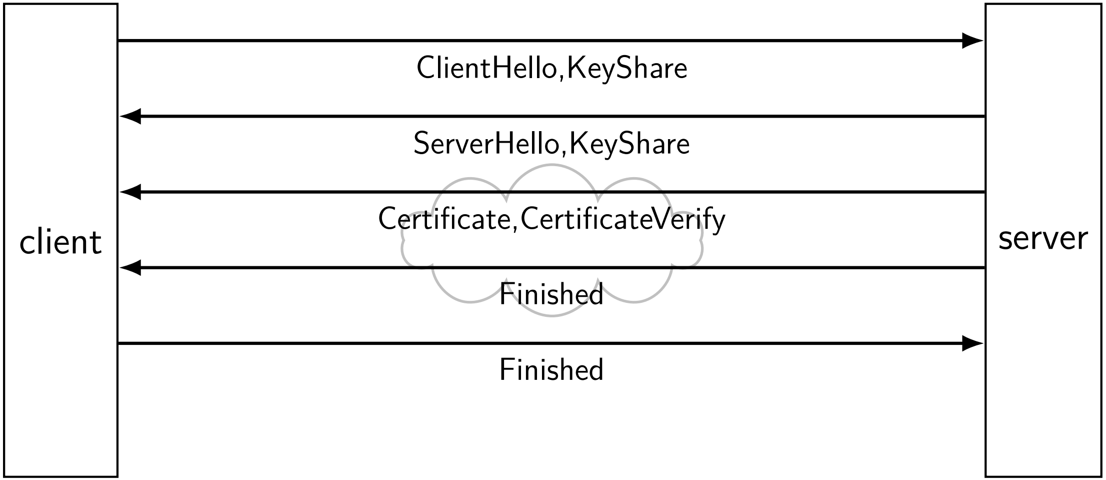
MAC(key made from key shares, Hash(everything so far))
(purpose: tie new key with rest of handshake)

typical TLS handshake



MAC(key made from key shares, Hash(everything so far))
(purpose: tie new key with rest of 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

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 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

…

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

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 — machine-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

...

link layer quality of service

if frame gets...

event	on Ethernet	on WiFi
collides with another	detected + may resend	resend
not received	lose silently	resent
header corrupted	usually discard silently	usually resend
data corrupted	usually discard silently	usually resend
too long	not allowed to send	not allowed to send
reordered (v. other messages)	received out of order	received out of order
destination unknown	lose silently	usually resend??
too much being sent	discard excess?	discard excess?

network layer quality of service

if packet ...

event	on IPv4/v6
collides with another	out of scope — handled by link layer
not received	lost silently
header corrupted	usually discarded silently
data corrupted	received corrupted
too long	dropped with notice or “fragmented” + recombined
reordered (v. other messages)	received out of order
destination unknown	usually dropped with notice
too much being sent	discard excess

network layer quality of service

if packet ...

event	on IPv4/v6
collides with another	out of scope — handled by link layer
not received	lost silently
header corrupted	usually discarded silently
data corrupted	received corrupted
too long	dropped with notice or “fragmented” + recombined
reordered (v. other messages)	received out of order
destination unknown	usually dropped with notice
too much being sent	discard excess

includes dropped by link layer
(e.g. if detected corrupted there)

firewalls

don’t want to expose network service to everyone?

solutions:

- service picky about who it accepts connections from
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- 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

...

t

querying the root

```
$ dig +trace +all www.cs.virginia.edu
...
edu.                            172800          IN          NS          b.edu-servers.net.
edu.                            172800          IN          NS          f.edu-servers.net.
edu.                            172800          IN          NS          i.edu-servers.net.
edu.                            172800          IN          NS          a.edu-servers.net.
...
b.edu-servers.net.          172800          IN          A          191.33.14.30
b.edu-servers.net.          172800          IN          AAAA          2001:503:231d::2:30
f.edu-servers.net.          172800          IN          A          192.35.51.30
f.edu-servers.net.          172800          IN          AAAA          2001:503:d414::30
...
;; Received 843 bytes from 198.97.190.53#53(h.root-servers.net) in 8 ms
...
```

querying the edu

```
$ dig +trace +all www.cs.virginia.edu
...
virginia.edu.                172800        IN        NS        nom.virginia.edu.
virginia.edu.                172800        IN        NS        uvaarpa.virginia.edu.
virginia.edu.                172800        IN        NS        eip-01-aws.net.virginia.edu.
nom.virginia.edu.        172800        IN        A        128.143.107.101
uvaarpa.virginia.edu.        172800        IN        A        128.143.107.117
eip-01-aws.net.virginia.edu. 172800 IN        A        44.234.207.10
;; Received 165 bytes from 192.26.92.30#53(c.edu-servers.net) in 40 ms
...
```

querying virginia.edu+cs.virginia.edu

```
$ dig +trace +all www.cs.virginia.edu
...
cs.virginia.edu.        3600        IN        NS        coresrv01.cs.virginia.edu.
coresrv01.cs.virginia.edu. 3600        IN        A        128.143.67.11
;; Received 116 bytes from 44.234.207.10#53(eip-01-aws.net.virginia.edu) in 72 ms

www.cs.Virginia.EDU.        172800        IN        A        128.143.67.11
cs.Virginia.EDU.        172800        IN        NS        coresrv01.cs.Virginia.EDU.
coresrv01.cs.Virginia.EDU. 172800 IN        A        128.143.67.11
;; Received 151 bytes from 128.143.67.11#53(coresrv01.cs.virginia.edu) in 4 ms
```

querying typical ISP's resolver

```
$ dig www.cs.virginia.edu
...
;; ANSWER SECTION:
www.cs.Virginia.EDU.          7183        IN        A        128.143.67.11
..
```

cached response

valid for 7183 more seconds

after that everyone needs to check again

‘connected’ UDP sockets

```
int fd = socket(AF_INET, SOCK_DGRAM, 0);
struct sockaddr_in my_addr= ...;
/* set local IP address + port */
bind(fd, &my_addr, sizeof(my_addr))
struct sockaddr_in to_addr = ...;
connect(fd, &to_addr); /* set remote IP address + port */
    /* doesn't actually communicate with remote address yet */
...
int count = write(fd, data, data_size);
// OR
int count = send(fd, data, data_size, 0 /* flags */);
    /* single message -- sent ALL AT ONCE */

int count = read(fd, buffer, buffer_size);
// OR
int count = recv(fd, buffer, buffer_size, 0 /* flags */);
    /* receives whole single message ALL AT ONCE */
```

UDP sockets on IPv4

```
int fd = socket(AF_INET, SOCK_DGRAM, 0);
struct sockaddr_in my_addr= ...;
/* set local IP address + port */
if (0 != bind(fd, &my_addr, sizeof(my_addr)))
    handle_error();
...
struct sockaddr_in to_addr = ...;
    /* send a message to specific address */
int bytes_sent = sendto(fd, data, data_size, 0 /* flags */,
    &to_addr, sizeof(to_addr));

struct sockaddr_in from_addr = ...;
    /* receive a message + learn where it came from */
int bytes_recvd = recvfrom(fd, &buffer[0], buffer_size, 0,
    &from_addr, sizeof(from_addr));
...
```

what about non-local machines?

when configuring network specify:

range of addresses to expect on local network

- 128.148.67.0-128.148.67.255 on my desktop
- “netmask”

gateway machine to send to for things outside my local network

- 128.143.67.1 on my desktop
- my desktop looks up the corresponding MAC address

routes on my desktop

```
$ /sbin/route -n
Kernel IP routing table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
0.0.0.0         128.143.67.1    0.0.0.0         UG    100    0        0 enp0s31f6
128.143.67.0    0.0.0.0         255.255.255.0   U     100    0        0 enp0s31f6
169.254.0.0     0.0.0.0         255.255.0.0     U     1000   0        0 enp0s31f6
```

network configuration says:

(line 2) to get to 128.143.67.0–128.143.67.255, send directly on local network

“genmask” is mask (for bitwise operations) to specify how big range is

(line 3) to get to 169.254.0.0–169.254.255.255, send directly on local network

(line 1) to get anywhere else, use “gateway” 128.143.67.1

querying the root

```
$ dig +trace +all www.cs.virginia.edu
...
edu.                        172800      IN       NS       b.edu-servers.net.
edu.                        172800      IN       NS       f.edu-servers.net.
edu.                        172800      IN       NS       i.edu-servers.net.
edu.                        172800      IN       NS       a.edu-servers.net.
...
b.edu-servers.net.        172800      IN       A        191.33.14.30
b.edu-servers.net.        172800      IN       AAAA        2001:503:231d::2:30
f.edu-servers.net.        172800      IN       A        192.35.51.30
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virginia.edu.                   172800          IN          NS          eip-01-aws.net.virginia.edu.
nom.virginia.edu.           172800          IN          A          128.143.107.101
uvaarpa.virginia.edu.           172800          IN          A          128.143.107.117
eip-01-aws.net.virginia.edu. 172800 IN          A          44.234.207.10
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querying virginia.edu+cs.virginia.edu

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coresrv01.cs.virginia.edu. 3600        IN        A        128.143.67.11
;; Received 116 bytes from 44.234.207.10#53(eip-01-aws.net.virginia.edu) in 72 ms

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;; ANSWER SECTION:
www.cs.Virginia.EDU.          7183        IN        A        128.143.67.11
..
```

cached response

valid for 7183 more seconds

after that everyone needs to check again

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
    /* or: addr.s_addr.in_addr = INADDR_LOOPBACK (127.0.0.1) */
    /* or: addr.s_addr.in_addr = htonl(...); */
addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
    /* or: addr.s_addr.in_addr = INADDR_LOOPBACK (127.0.0.1) */
    /* or: addr.s_addr.in_addr = htonl(...); */
addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen
...
int sc
```

INADDR_ANY: accept connections for any address I can!

alternative: specify specific address

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
    /* or: addr.s_addr.in_addr = INADDR_LOOPBACK (127.0.0.1) */
    /* or: addr.s_addr.in_addr = htonl(...); */
addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
lis
...
int
```

bind to 127.0.0.1? only accept connections from same machine
what we recommend for FTP server assignment

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
    /* or: addr.s_addr.in_addr = INADDR_LOOPBACK (127.0.0.1) */
    /* or: addr.s_addr.in_addr = htonl(...); */
addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen(serv
...
int socket_fd = accept(server_socket_fd, NULL);
```

choose the number of unaccepted connections

connection setup: client — manual addresses

```
int sock_fd;

server = /* code on later slide */;
sock_fd = socket(
    AF_INET, /* IPv4 */
    SOCK_STREAM, /* byte-oriented */
    IPPROTO_TCP
);
if (sock_fd < 0) { /* handle error */ }

struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = htonl(2156872459); /* 128.143.67.11 */
addr.sin_port = htons(80); /* port 80 */
if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client — manual addresses

```c
int sock_fd;

server = /* code on later slide */;
sock_fd = socket(
    AF_INET, /* IPv4 */
    SOCK_STREAM, /* byte-oriented */
    IPPROTO_TCP
);
if (sock_fd < 0) { /* handle error */ }
```

specify IPv4 instead of IPv6 or local-only sockets

specify TCP (byte-oriented) instead of UDP (‘datagram’ oriented)

```c
st
ad
addr.sin_addr.s_addr = htonl(2156872459); /* 128.143.67.11 */
addr.sin_port = htons(80); /* port 80 */
if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client — manual addresses

```
int sock_fd;

server = /* cod
sock_fd = socke
    AF_INET, /*
    SOCK_STREAM, /* byte-oriented */
    IPPROTO_TCP
);
if (sock_fd < 0) { /* handle error */ }

struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = htonl(2156872459); /* 128.143.67.11 */
addr.sin_port = htons(80); /* port 80 */
if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

htonl/s = host-to-network long/short
network byte order = big endian

connection setup: client — manual addresses

```
int sock_fd;

server = /
sock_fd =
    AF_INE
    SOCK_S
    IPPROTO_TCP
);
if (sock_fd < 0) { /* handle error */ }

struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = htonl(2156872459); /* 128.143.67.11 */
addr.sin_port = htons(80); /* port 80 */
if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

struct representing IPv4 address + port number
declared in `<netinet/in.h>`
see `man 7 ip` on Linux for docs

echo client/server

```
void client_for_connection(int socket_fd) {
    int n; char send_buf[MAX_SIZE]; char recv_buf[MAX_SIZE];
    while (prompt_for_input(send_buf, MAX_SIZE)) {
        n = write(socket_fd, send_buf, strlen(send_buf));
        if (n != strlen(send_buf)) {...error?...}
        n = read(socket_fd, recv_buf, MAX_SIZE);
        if (n <= 0) return; // error or EOF
        write(STDOUT_FILENO, recv_buf, n);
    }
}
```

```
void server_for_connection(int socket_fd) {
    int read_count, write_count; char request_buf[MAX_SIZE];
    while (1) {
        read_count = read(socket_fd, request_buf, MAX_SIZE);
        if (read_count <= 0) return; // error or EOF
        write_count = write(socket_fd, request_buf, read_count);
        if (read_count != write_count) {...error?...}
    }
}
```

echo client/server

```
void client_for_connection(int socket_fd) {
    int n; char send_buf[MAX_SIZE]; char recv_buf[MAX_SIZE];
    while (prompt_for_input(send_buf, MAX_SIZE)) {
        n = write(socket_fd, send_buf, strlen(send_buf));
        if (n != strlen(send_buf)) {...error?...}
        n = read(socket_fd, recv_buf, MAX_SIZE);
        if (n <= 0) return; // error or EOF
        write(STDOUT_FILENO, recv_buf, n);
    }
}
```

```
void server_for_connection(int socket_fd) {
    int read_count, write_count; char request_buf[MAX_SIZE];
    while (1) {
        read_count = read(socket_fd, request_buf, MAX_SIZE);
        if (read_count <= 0) return; // error or EOF
        write_count = write(socket_fd, request_buf, read_count);
        if (read_count != write_count) {...error?...}
    }
}
```

echo client/server

```
void client_for_connection(int socket_fd) {
    int n; char send_buf[MAX_SIZE]; char recv_buf[MAX_SIZE];
    while (prompt_for_input(send_buf, MAX_SIZE)) {
        n = write(socket_fd, send_buf, strlen(send_buf));
        if (n != strlen(send_buf)) {...error?...}
        n = read(socket_fd, recv_buf, MAX_SIZE);
        if (n <= 0) return; // error or EOF
        write(STDOUT_FILENO, recv_buf, n);
    }
}
```

```
void server_for_connection(int socket_fd) {
    int read_count, write_count; char request_buf[MAX_SIZE];
    while (1) {
        read_count = read(socket_fd, request_buf, MAX_SIZE);
        if (read_count <= 0) return; // error or EOF
        write_count = write(socket_fd, request_buf, read_count);
        if (read_count != write_count) {...error?...}
    }
}
```

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags = AI_PASSIVE;

rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }
```

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags =

rv = getaddrinfo                                          rver);
if (rv != 0) { /
```

hostname could also be NULL
means “use all possible addresses”
only makes sense for servers

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags

rv = getaddrin                                              er);
if (rv != 0) {
```

portname could also be NULL

means "choose a port number for me"

only makes sense for servers

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *ho
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags = AI_PASSIVE;

rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }
```

AI_PASSIVE: “I’m going to use bind”

connection setup: server, addrinfo

```
struct addrinfo *server;
... getaddrinfo(...) ...

int server_socket_fd = socket(
    server->ai_family,
    server->ai_socktype,
    server->ai_protocol
);

if (bind(server_socket_fd, ai->ai_addr, ai->ai_addr_len)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_protocol
     //
);
if (soc
if (cor                                                  < 0) {
    /*
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

addrinfo contains all information needed to setup socket

set by `getaddrinfo` function (next slide)

handles IPv4 and IPv6

handles DNS names, service names

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addr

sock_fd = so
    server->
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

ai_addr points to struct representing address
type of struct depends whether IPv6 or IPv4

connection setup: client, using addrinfo

since addrinfo contains pointers to dynamically allocated memory, call this function to free everything

```
int sock_fd;
st
 
so
 
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.ai_family = AF_INET4; /* for IPv4 only */

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.a

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

NB: pass pointer *to pointer* to addrinfo to fill in

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const
...
struct
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.ai_family = AF_INET4; /* for IPv4 only */

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

AF_UNSPEC: choose between IPv4 and IPv6 for me

AF_INET, AF_INET6: choose IPv4 or IPV6 respectively

connection setup: multiple server addresses

```
struct addrinfo *server;
...
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

for (struct addrinfo *current = server; current != NULL;
      current = current->ai_next) {
    sock_fd = socket(current->ai_family, current->ai_socktype, curr
    if (sock_fd < 0) continue;
    if (connect(sock_fd, current->ai_addr, current->ai_addrlen) ==
        break;
    }
    close(sock_fd); // connect failed
}
freeaddrinfo(server);
DoClientStuff(sock_fd);
close(sock_fd);
```

connection setup: multiple server addresses

```
struct addrinfo *server;
...
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

for (struct addrinfo *current = server; current != NULL;
        current = current->ai_next) {
    sock_fd = socket(current->ai_family, current->ai_socktype, curr
    if (sock_fd < 0) continue;
    if (connect(sock_fd, current->ai_addr, current->ai_addrlen) ==
        break;
    }
    clos
}
freeaddr
DoClient
close(so
```

addrinfo is a linked list

name can correspond to multiple addresses

example: redundant copies of web server

example: an IPv4 address and IPv6 address

example: wired + wireless connection on one machine

connection setup: old lookup function

```
/* example hostname, portnum= "www.cs.virginia.edu", 443*/
const char *hostname; int portnum;
...
struct hostent *server_ip;
server_ip = gethostbyname(hostname);

if (server_ip == NULL) { /* handle error */ }

struct sockaddr_in addr;
addr.s_addr = *(struct in_addr*) server_ip->h_addr_list[0];
addr.sin_port = htons(portnum);
sock_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
connect(sock_fd, &addr, sizeof(addr));
...
```

aside: on server port numbers

Unix convention: must be `root` to use ports 0–1023

  root = superuser = ‘adminstrator user’ = what sudo does

so, for testing: probably ports > 1023