NETWORKING!
ACK!

A COMPUTER NETWORKING ZINE!

BY JULIA EVANS!

THERE'S SO MUCH NETWORKING STUFF TO LEARN! OMG!

HEY, IT'S NOT SO BAD! LET'S LEARN THE IDEAS ONE AT A TIME!

NETWORKING ISN'T MAGIC, BUT I SURE FEEL LIKE A WIZARD NOW!

like this?
you can print more!
for free!
http://jvns.ca/zines

cast of characters

in your house

your laptop
(that you use
to look at cats)

cool.py
your
program

operating
system
(knows how to
do networking)

WRT
your home
router

computers you'll talk to

jvns.ca
server
(has cat
picture)

DNS
DNS server
(knows which
server hosts
jvns.ca)

the cat picture
we're downloading

in the middle

intermediate routers
on the internet

TCP
UDP
UDP
TCP

packets!
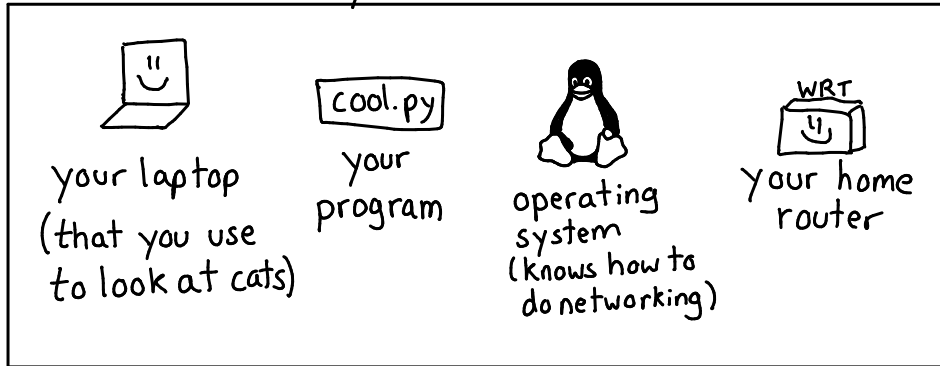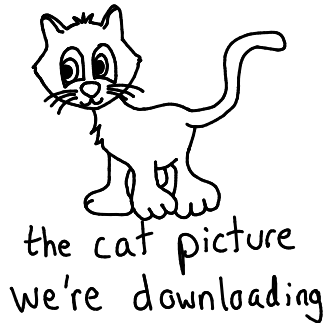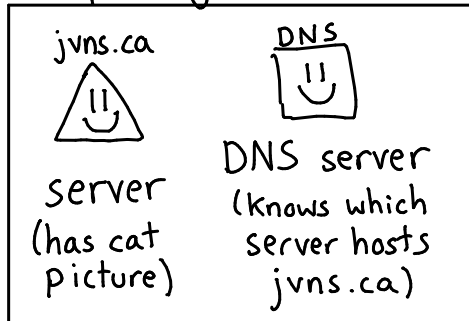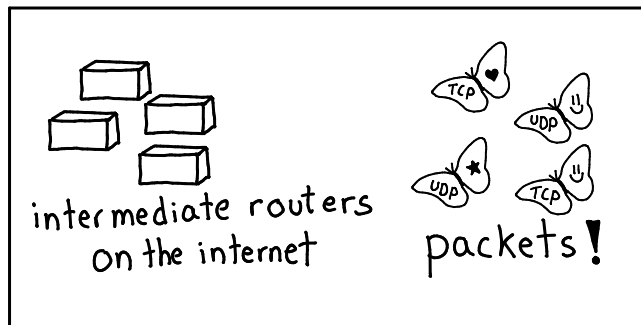
♡ thanks ♡
for reading

If you want to know more about networking:

→ make network requests! play with

dig   traceroute   tcpdump   ifconfig

netcat   wireshark   netstat

→ beej's guide to network programming is
a useful + funny guide to the socket
API on Unix systems.

→ beej.us /guide /bgnet ←

→ High Performance Browser Networking
is a ★fantastic★ and practical guide
to what you need to know about networking
to make fast websites.
You can read it for free at:

→ hpbn.co ←

Thanks to Kamal Marhubi, Chris Kanich, and
and Ada Munroe for reviewing this!

Cover art by the amazing Liz Baillie

wireshark

Wireshark is an {amazing} tool for packet analysis. Here's an exercise to learn it! Run this:

```
sudo tcpdump port 80 -w http.pcap
```

While that's running, open metafilter.com in your browser. Then press Ctrl + C to stop tcpdump. Now we have a pcap!
Open http.pcap with Wireshark.

Some questions you can try to answer:

① What HTTP headers did your browser send to metafilter.com?
(hint: search `frame contains "GET"`)

② How many packets were exchanged with metafilter.com's server?
(hint: search `ip-dst == 54.1.2.3`) put the IP from "ping metafilter.com" here

Wireshark makes it easy to look at:
- IP addresses and ports
- SYNs and ACKs for TCP traffic
- exactly what's happening with DNS requests
- and so much more. It's a great way to poke around and learn.

What's this?!

hi! I'm Julia
twitter: @b0rk
blog: http://jvns.ca

I put a picture of a cat on the internet here:
✳ `jvns.ca/cat.png` ✳ (go look!)

In this zine we'll learn everything (mostly) that needs to happen to get that cat picture from my server to your laptop.

My goal is to help get you from

"I've heard about some of these HTTP/DNS/TCP things but I don't understand how they work exactly or how they all fit together" ← me after I'd been working as a web developer for a year
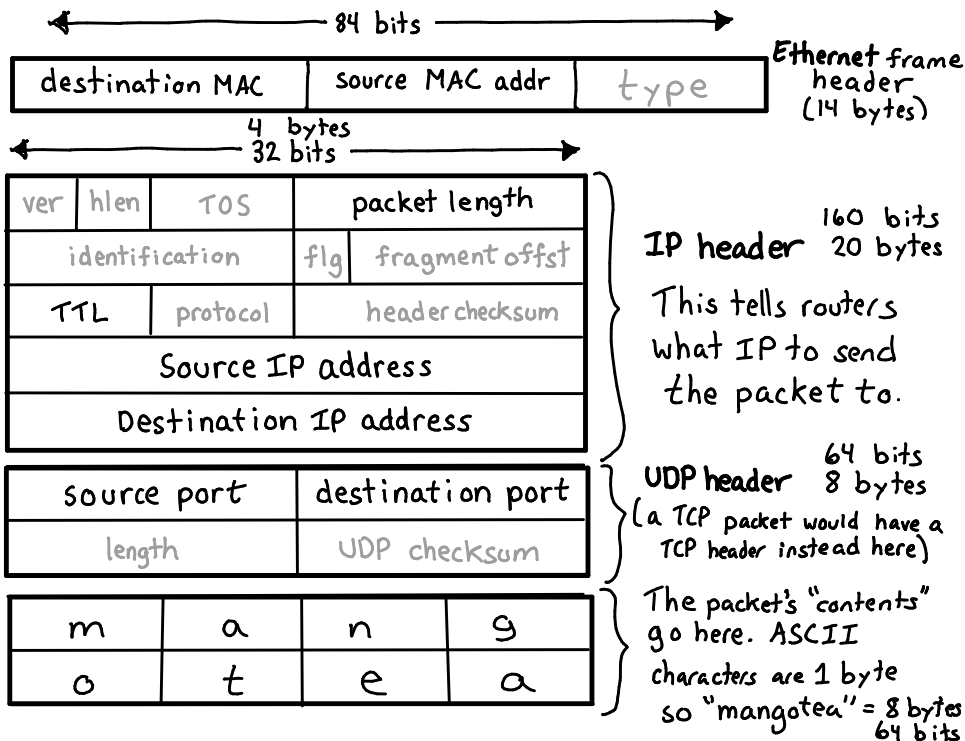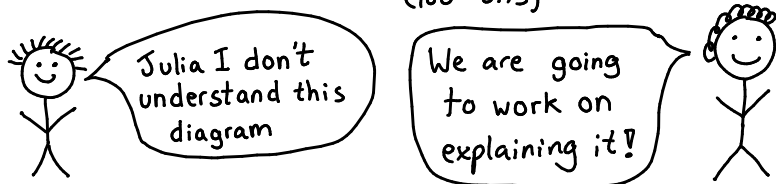
to...

there's a networking problem! I totally know where to start! ← me now

our star: the packet

All data is sent over the internet in {packets}. A packet is a series of bits (01001011011....) and it's split into sections (or "headers")
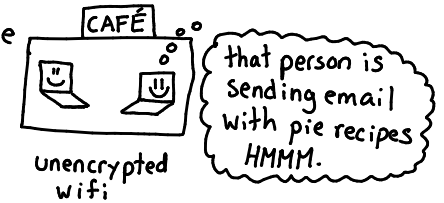
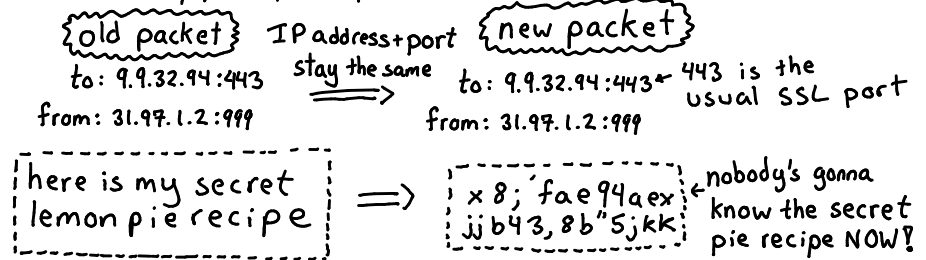Here's what a UDP packet that says "mangotea" looks like. It's 50 bytes in all! (400 bits)

Julia I don't understand this diagram
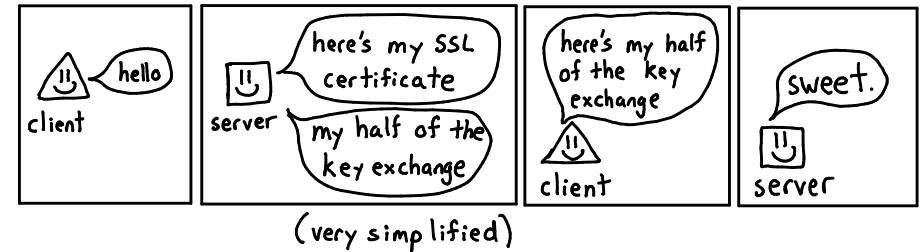
We are going to work on explaining it!

← 84 bits →

destination MAC	Source MAC addr	type

Ethernet frame header (14 bytes)

4 bytes
← 32 bits →

ver	hlen	TOS	packet length
identification		flg	fragment offst
TTL	protocol		header checksum
Source IP address			
Destination IP address			

IP header 160 bits 20 bytes

This tells routers what IP to send the packet to.

source port	destination port
length	UDP checksum

UDP header 64 bits 8 bytes
(a TCP packet would have a TCP header instead here)

m	a	n	g
o	t	e	a

The packet's "contents" go here. ASCII characters are 1 byte so "mangotea" = 8 bytes 64 bits

---

SSL/TLS
(TLS: newer version of SSL)

When you send a packet on the internet, LOTS of people can potentially read it.

unencrypted wifi

that person is sending email with pie recipes HMMM.

SSL encrypts your packets:

{old packet}   IP address+port   {new packet}
to: 9.9.32.94:443   stay the same   to: 9.9.32.94:443 ← 443 is the usual SSL port
from: 31.97.1.2:999   from: 31.97.1.2:999

here is my secret lemon pie recipe ⟹ x8; fae94aex jjb43,8b"5jkk ← nobody's gonna know the secret pie recipe NOW!

What happens when you go to https://jvns.ca:

client *hello*	server *here's my SSL certificate* *my half of the key exchange*	*here's my half of the key exchange* client	*sweet.* server

(very simplified)

Once the client and server agree on a key for the session, they can encrypt all the communication they want.

To see the certificate for jvns.ca, run:

```
$ openssl s_client -connect jvns.ca:443 -servername jvns.ca
```

TLS is really complicated. You can use a tool like SSL Labs to check the security of your site.

Notation time!

10.0.0.0/8   132.5.23.0/24

People describe groups of IP addresses using **CIDR notation**.

example CIDRs

CIDR	range of IPs
10.0.0.0/8	10.*.*.*
10.9.0.0/16	10.9.*.*
10.9.8.0/24	10.9.8.*

important examples

10.0.0.0/8 and 192.168.0.0/16 and 172.16.0.0/12 are reserved for local networking.

In CIDR notation, a /n gives you 2^{32-n} IP addresses. So a /24 is $2^8 = 256$ IPs.

It's important to represent groups of IP addresses efficiently because routers have LOTS TO DO.

router

ooo *is 192.168.3.2 in the subnet 192.168.0.0/16? I can do some really fast bit arithmetic and find out!*

10.9.0.0 is this in binary:
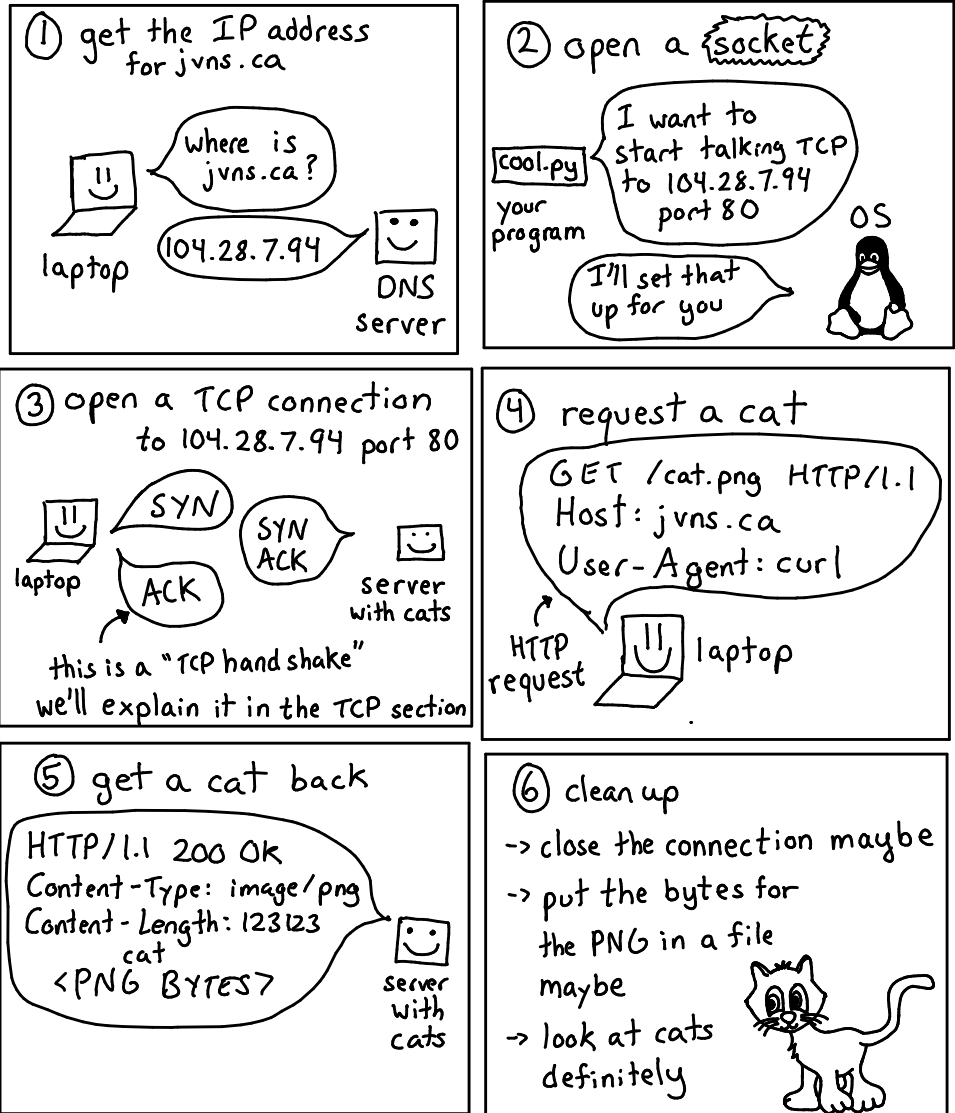
00001010 00001001 00000000 00000000

^ first 24 bits

10.9.0.0/24 is all the IP addresses which have the same first 24 bits as 10.9.0.0!

steps to get a cat picture

from jvns.ca/cat.png

When you download an image, there are a LOT of networking moving pieces. Here are the basic steps we'll explain in the next few pages.

① get the IP address for jvns.ca

laptop — *where is jvns.ca?*
104.28.7.94 — DNS server

② open a socket

cool.py (your program) — *I want to start talking TCP to 104.28.7.94 port 80*
OS — *I'll set that up for you*

③ open a TCP connection to 104.28.7.94 port 80

laptop — SYN → SYN ACK ← server with cats
ACK →

this is a "TCP handshake" we'll explain it in the TCP section

④ request a cat

GET /cat.png HTTP/1.1
Host: jvns.ca
User-Agent: curl

HTTP request — laptop

⑤ get a cat back

HTTP/1.1 200 Ok
Content-Type: image/png
Content-Length: 123123
cat
<PNG BYTES>

server with cats

⑥ clean up
-> close the connection maybe
-> put the bytes for the PNG in a file maybe
-> look at cats definitely

DNS

★ ★ Step ① : get the IP address for jvns.ca ★ ★ ★

All networking happens by sending <u>packets</u>. To send a packet to a server on the internet, you need an {IP address} like 104.28.7.94

jvns.ca and google.com are domain names. DNS (the "Domain Name System") is the protocol we use to get the IP address for a domain name.

laptop — what's the IP for jvns.ca? — DNS request

DNS response — it's 104.28.7.94 — DNS server
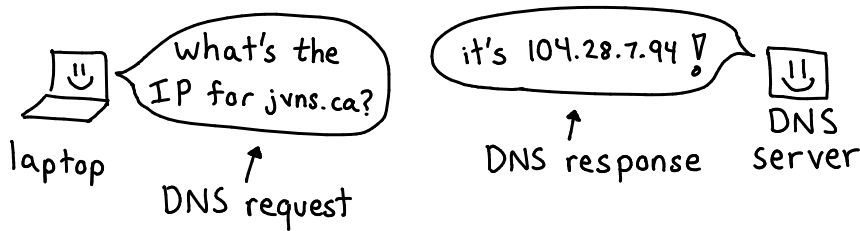
The DNS request + response are both usually UDP packets.

When you run `$ curl jvns.ca/cat.png` :

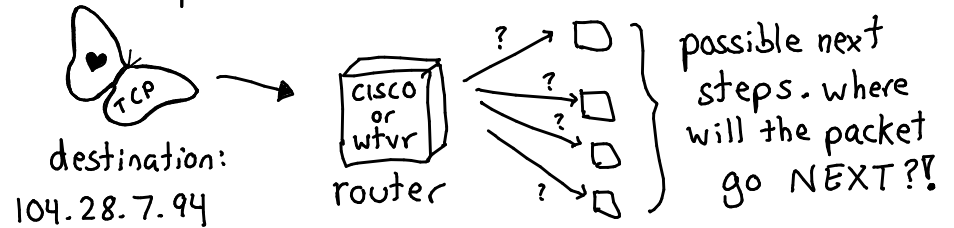| curl calls the "getaddrinfo" function with "jvns.ca"	getaddrinfo finds the system DNS server (like 8.8.8.8)	getaddrinfo makes a request to that server	✿ IP address: obtained ! ★ 104.28.7.94

Your system's default DNS server is often configured in /etc/resolv.conf.

8.8.8.8 is Google's DNS server, and lots of people use it. It's a great choice!

How packets get sent across the ocean

I have a packet for 104.28.7.9 but how do I get through all this INTERNET

we got it!

your laptop — home router — intermediate routers — cable under the OCEAN — 104.28.7.94 server
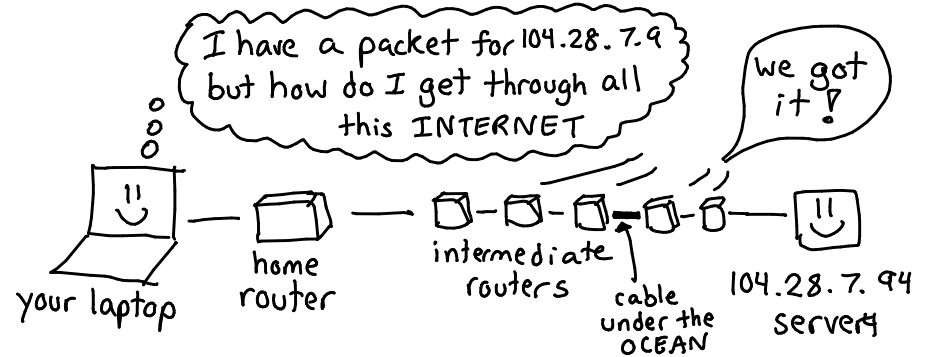
When a packet arrives at a router

TCP

destination: 104.28.7.94

cisco or wtvr router

? ? ? ? possible next steps. where will the packet go NEXT?!

Routers use a protocol called {BGP} to decide what router the packet should go to next:

A packet can take a <u>lot</u> of different routes to get to the same destination!
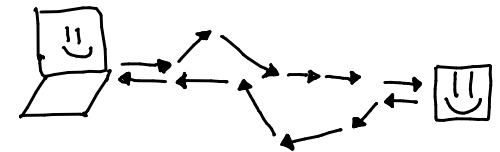
The route it takes to get from A→B might be different from B→A.

Exercise: Run `traceroute google.com` to see what steps your packet takes to get to google.com.
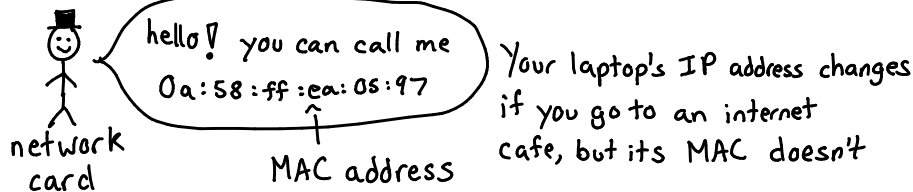
Local networking

how to talk to a computer in the same room

Every computer is in a <u>subnet</u>. Your subnet is the <u>list of computers</u> you can talk to directly.

printer · your laptop · your phone · router · REST OF WORLD
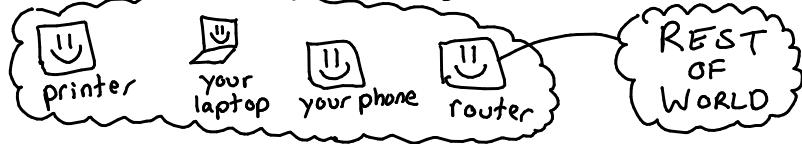
What does it mean to talk "directly" to another computer? Well, every computer on the internet has a network card with a MAC address.

hello! you can call me 0a:58:ff:ea:05:97

network card

↑ MAC address

Your laptop's IP address changes if you go to an internet cafe, but its MAC doesn't

When you send a packet to a computer in your subnet, you put the computer's MAC address on it. To get the right MAC, your computer uses a protocol called ARP: (Address Resolution Protocol)

who's 192.168.0.100?

It's me! 68:c4:4d:89:4c:11!

I will store that in my ARP table!
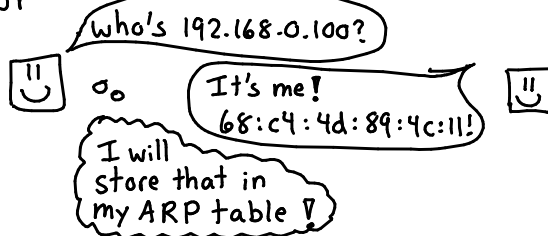
You can run `arp -na` to see the contents of the ARP table on your computer. It should look like this:

MAC for 192.168.1.120 (my printer)

my wifi card

```
$ arp -na
? (192.168.1.120) at 94:53:30:91:98:c8 [ether] on wlp3s0
```

There are 2 kinds of DNS servers:

recursive

I can get you an IP address for ANY website by asking the right authoritative server

DNS

authoritative

wanna know where jvns.ca is? Talk to ME!

DNS server (like art.ns.cloudflare.com)

When you query a recursive DNS server, here's what happens:

I have to talk to THREE authoritative DNS servers? Okay!

recursive DNS server

the recursive DNS server keeps a permanent list of root servers

where's jvns.ca?   ask there!   root DNS server a.root-servers.net

where's jvns.ca?   ask there!   .ca DNS server j.ca-servers.ca

where's jvns.ca?   jvns.ca DNS server art.ns.cloudflare.com
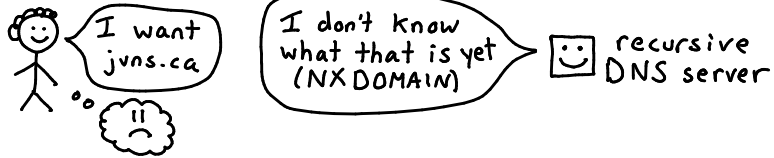
104.28.7.94 and 104.28.6.94
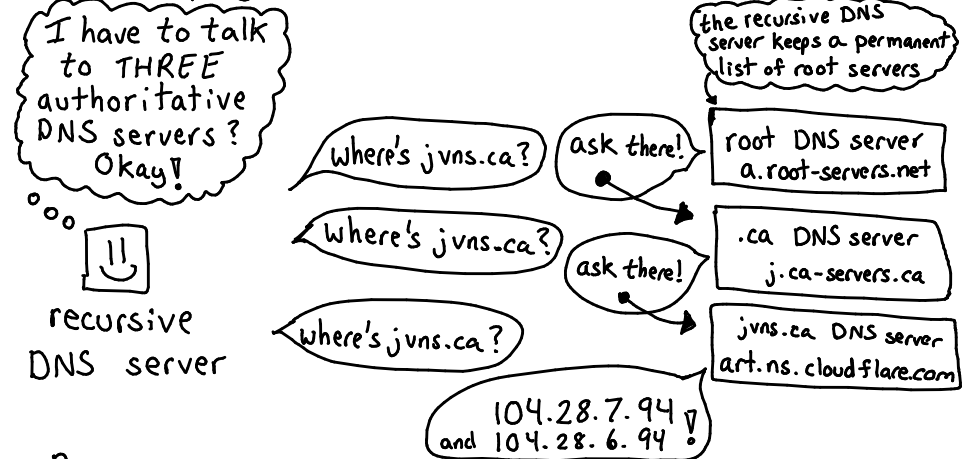
Recursive DNS servers usually cache DNS records. Every DNS record has a TTL ("time to live") that says how long to cache it for. You often can't force them to update their cache. You just have to wait:

I updated my DNS records, but when I visit the site in my browser I see the old version !!

20 minutes later after the recursive DNS server cache updates...

everything is great now
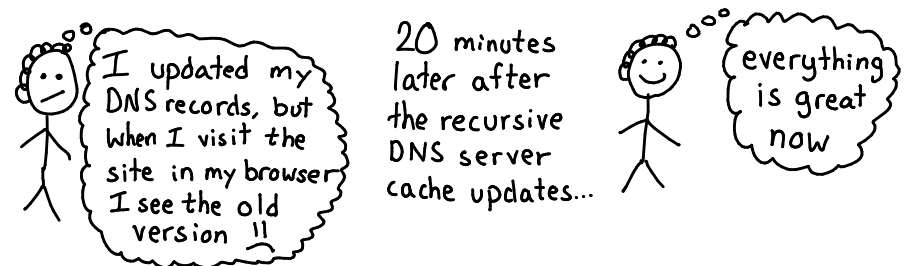
let's make ♡ DNS requests ♡

When you're setting up DNS for a new domain, often this happens

I want jvns.ca

I don't know what that is yet (NX DOMAIN) — recursive DNS server

Here's how you can make DNS queries from the command line to understand what's going on:

```
$ dig jvns.ca

;; ANSWER SECTION
jvns.ca   268  IN  A  104.28.6.94
jvns.ca   268  IN  A  104.28.7.94

;; SERVER 127.0.1.1#53
```

there can be lots of IP addresses for one domain

this record expires after 268 seconds

an "A" record is an IP address

the DNS server I'm using

```
$ dig @ 8.8.8.8 jvns.ca
```

8.8.8.8 is Google's recursive DNS server. @8.8.8.8 queries that instead of the default.

```
$ dig +trace jvns.ca

.           502441  IN  NS   h.root-servers.net
ca.         172800  IN  NS   c.ca-servers.net
jvns.ca.    86400   IN  NS   art.ns.cloudflare.com
jvns.ca.    300     IN  A    104.28.6.94
```

root DNS server !

dig +trace basically does the same thing a recursive DNS server would do to find your domain's IP

these are the 3 authoritative servers a recursive server has to query to get an IP for jvns.ca

UDP
user datagram protocol

DNS sends requests using UDP. UDP is a really simple protocol. The packets look like this:

~ IP stuff ~

UDP header →

source port	destination port
length	UDP checksum

~ packet contents ~
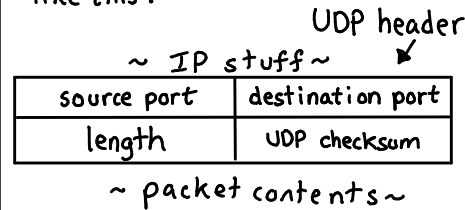
"unreliable data protocol" (not what it really stands for)

When you send UDP packets, they might arrive
- out of order
- never

any packet can actually get lost, but UDP won't do anything to help you.

Packet sizes are limited

I'm gonna put 3000 characters in this packet

nope that won't fit. 1500 bytes is probably a better size. *

* packet sizes are actually a super interesting topic. Search "MTU"

you need to decide how to organize your data into packets manually

Ok, 623 bytes in this packet, 747 bytes in that one...

VPNs use UDP

hi I want to talk to 12.12.12.12

Ok stuff all your data into a UDP packet, send it to me, I'll pass it along. — VPN server
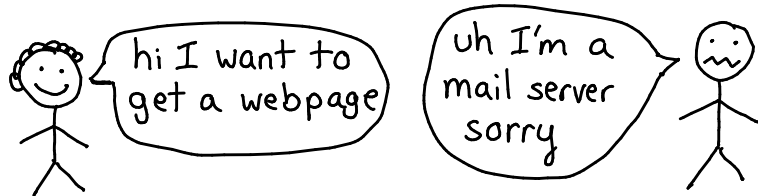
Streaming video often uses UDP

Read http://hpbn.co/webrtc for a GREAT discussion of using UDP in a real time protocol.

What's a :port: ?

ports are part of the TCP and UDP protocols
(TCP port 999 and UDP port 999 are different)

When you send a TCP message, you want
to talk to a specific kind of program
This would be bad:

"hi I want to get a webpage"

"uh I'm a mail server sorry"

We want to have different kinds of programs
on the same server: minecraft DNS email

So every TCP packet has a port number
between 1 and 65535 on it:

"I'm listening on TCP port 80"

"here's a TCP packet with port 80 on it!"

"Ooh! that's for ME!"

netstat and lsof can tell you which ports are in use on your computer

Some common ports:

DNS: UDP port 53
HTTP: TCP port 80
HTTPS: TCP port 443
SMTP: TCP port 25 (mail)
Minecraft: TCP+UDP 25565

Sockets

Step ②: now that we have an IP address,
the next step is to open a socket!
Let's learn what that is.

your program doesn't know how to do TCP

"idk what "TCP" is I just want to get a webpage"

code.py Program

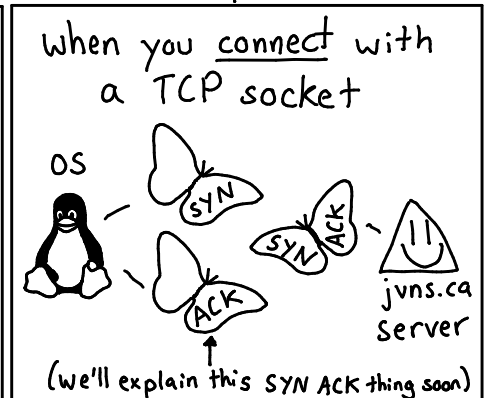"don't worry! I can help!" OS

what using sockets is like

step 1: ask the OS for a socket
step 2: connect the socket to an IP address and port
step 3: write to the socket to send data

4 common socket types

TCP — to use TCP

UDP — to use UDP

raw — for ULTIMATE POWER. ping uses this to send ICMP packets

unix — to talk to programs on the same computer

When you connect with a TCP socket

OS

SYN

SYN ACK

ACK

jvns.ca server

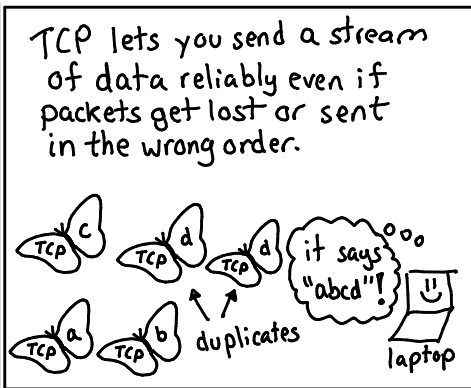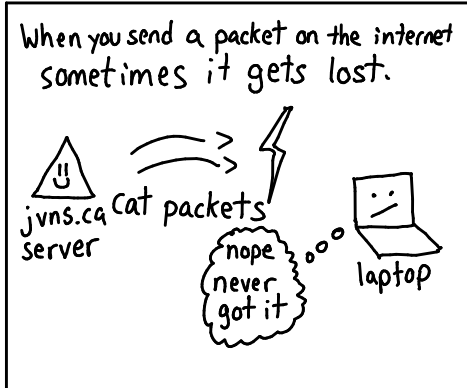(we'll explain this SYN ACK thing soon)

When you write to a socket

code.py program → writes lots of data ♥♥♥♥♥

→ splits it up → into packets to send it

"this socket interface is great! the operating system does so much for me!"

TCP: how to reliably get a cat

Step ③ in our plan is "open a TCP connection!"

Let's learn what this "TCP" thing even is ☺

When you send a packet on the internet sometimes it gets lost.

jvns.ca server — Cat packets — "nope never got it" — laptop

TCP lets you send a stream of data reliably even if packets get lost or sent in the wrong order.

TCP c, TCP d, TCP d, TCP a, TCP b → duplicates — "it says 'abcd'!" laptop

how does TCP work, you ask? WELL!

how to know what <u>order</u> the packets should go in:

Every packet says what <u>range of bytes</u> it has
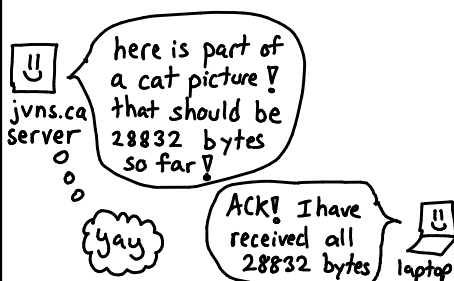
Like this:
- once upon a ti ← bytes 0-13
- agical oyster ← bytes 30-42
- me there was a m ← bytes 14-29

Then the client can assemble all the pieces into:
"Once upon a time there was a magical oyster"

The position of the first byte (0, 14, 30 in our example) is called the "sequence number"

how to deal with lost packets:

When you get TCP data, you have to <u>acknowledge</u> it: (ACK)

jvns.ca server — "here is part of a cat picture! that should be 28832 bytes so far!"

yay

"ACK! I have received all 28832 bytes" laptop

If the server doesn't get an ACKnowledgement, it will <u>retry</u> sending the data.

---

networking layers

"I don't always find this useful but it's good to know what "layer 4" means"
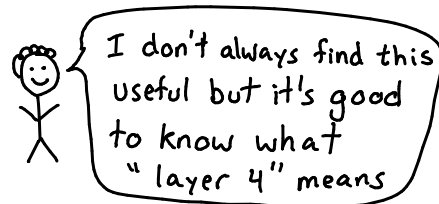
Networking layers mostly correspond to different sections of a packet.
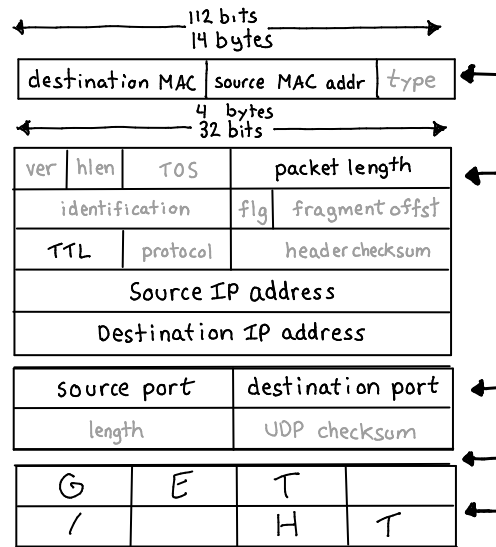
Layer 1: wires + radio waves

Layer 2: Ethernet/wifi protocol. Your **network card** understands it.

← 112 bits / 14 bytes →		
destination MAC	source MAC addr	type

← 4 bytes / 32 bits →			
ver	hlen	TOS	packet length
identification		flg	fragment offst
TTL		protocol	header checksum
Source IP address			
Destination IP address			

Layer 3: IP addresses
routers look at this a lot to decide where to send the packet next.

source port	destination port
length	UDP checksum

Layer 4: TCP or UDP
Where you get your ports!

G	E	T
/		H	T

Layer 5+6: don't really exist here (though people call SSL "layer 5")

Layer 7: HTTP and friends
Routers ignore this layer mostly. DNS queries, emails, etc. go here.

layer 3 networking tool
↑
ignores layer 4 and above

"I only know about IP addresses! I don't even know what a port is let alone what the packet says"

Your home router looks at layers 2+3+4

Your <u>applications</u> mostly worry about layer 7 but they get to tell the operating system what IP and port to use.

The <u>network card</u> in your computer only cares about layers 1+2.
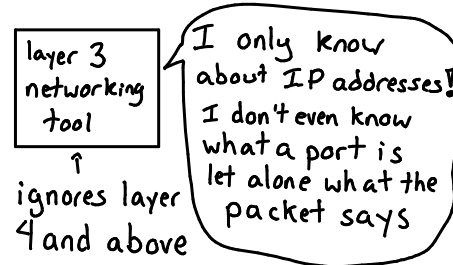
The cool thing is that the layers are mostly independent of each other — you can change the IP address (layer 3) and not worry about layers 4+7

☆☆ ... and now for even MORE ♡♡♡
☆☆ ♡♡♡

We've covered the basics of how to download a cat picture now! But there's a lot more to know! Let's talk about a few more topics.

We'll explain a little more about networking protocols:

- what a **port** actually is
- how a **packet** is put together
- security: how SSL works
- the different **networking layers**
- **UDP** and why it's amazing

and how packets get sent from place to place:

- how packets get sent in a **local network**
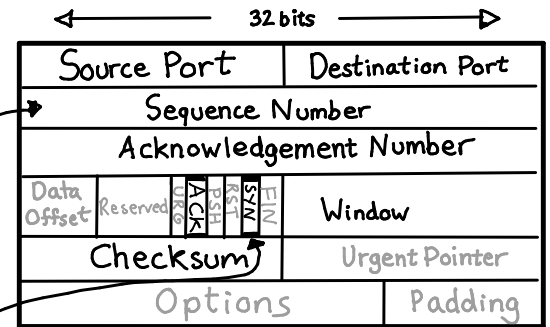- and how packets get from **your house to jvns.ca**
- networking **notation**

let's learn MORE!

This is what a TCP header looks like:

the "sequence number" lets you assemble packets in the right order ☺

32 bits	
Source Port	Destination Port
Sequence Number	
Acknowledgement Number	
Data Offset · Reserved · URG · ACK · PSH · RST · SYN · FIN	Window
Checksum	Urgent Pointer
Options	Padding

this is the SYN bit

Every TCP connection starts with a "handshake". This makes sure both sides of the connection can communicate with each other.

client   server

SYN → SYN ACK → ACK
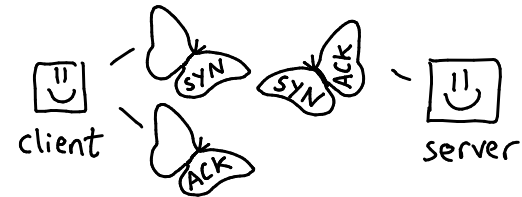
But what do "SYN" and "ACK" mean? Well! TCP headers have 6 bit flags (SYN, ACK, RST, FIN, PSH, URG) that you can set (you can see them in the diagram.) A SYN packet is a packet with the SYN flag set to 1.

When you see "connection refused" or "connection timeout" errors, that means the TCP handshake didn't finish!

I ran `sudo tcpdump host jvns.ca` in one and `curl jvns.ca` in another. This is some of the output:

```
localhost:51104 > 104.28.6.94:80    Flags [S]
104.28.6.94:80  > localhost:51104   Flags [S.]
localhost:51104 > 104.28.6.94:80    Flags [.]
```

TCP handshake!

jvns.ca IP address

S is for SYN
. is for ACK

HTTP

Step 4: Finally, we can request cat.png!

Every time you get a webpage or see an image online, you're using ⌐HTTP¬

HTTP is a pretty simple plaintext protocol. In fact, it's __so__ simple that you can make a HTTP request by hand right now. Let's do it ‼‼

First, let's make a file called request.txt

```
GET / HTTP/1.1
Host: ask.metafilter.com
User-Agent: zine
(put 2 newlines at the end)
```
← we'll explain this Host: bit later

Then:

```
cat request.txt | nc metafilter.com 80
```

the [nc] command ("netcat") sets up a TCP connection to metafilter.com and sends the HTTP request you wrote! The response we get back looks like:

```
200 OK
Content-Length: 120321
··· headers ···
a bunch of
HTML
```

HTTP/2 is the next version of HTTP. It's very different but we're out of space.

important HTTP headers

This is a HTTP request:
```
GET /cat.png HTTP/1.1
Host: jvns.ca
User-Agent: zine
```

The User-Agent: and Host: lines are called "headers". They give the webserver extra information about what webpage you want!

{the Host header} ← my favorite!

GET /

GET / Host: jvns.ca

dude, do you even know how many websites I serve? You gotta be more specific.

jvns.ca Server

NOW we're talking

Most servers serve __lots__ of different websites. The Host header lets you pick the one you want!

Servers also send __response__ headers with extra information about the response.

More useful headers:

{User-Agent}
Lots of servers use this to check if you're using an old browser or if you're a bot.

{Accept-Encoding}
Want to save bandwidth? Set this to "gzip" and the server might compress your response.

{Cookie}
When you're logged into a website, your browser sends data in this header! This is how the server knows you're logged in.