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

NETWORKiNG!

ACK!

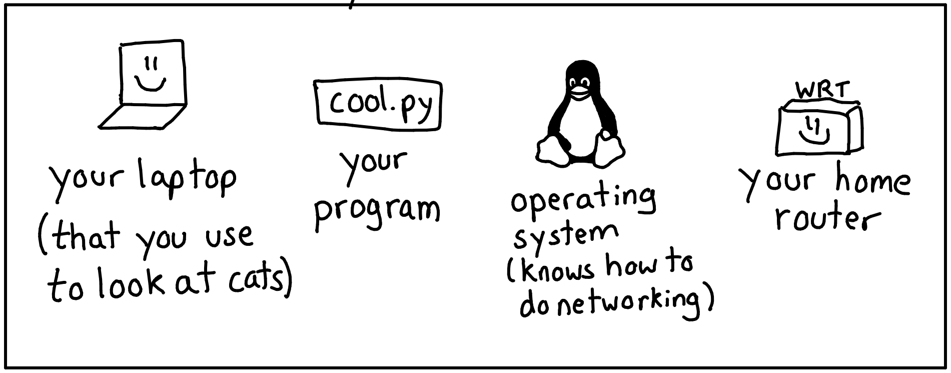
A COMPUTER NETWORKING ZINE!

BY JULIA EVANS!

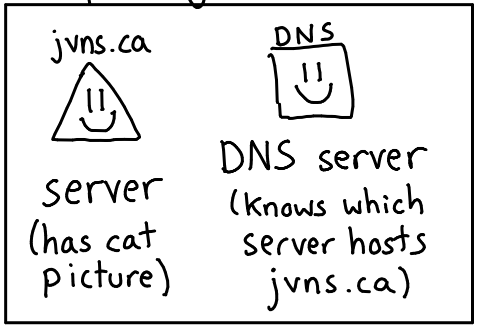
TCPARP
pack
TTL
socket
namese
THERE'S SO MUCH NETWORKING STUFF TO LEARN! OMG!
HEY, IT'S NOT SO BAD! LET'S LEARN THE IDEAS ONE AT A TIME!
NETWORKING ISN'T MAGIC, BUT I SURE FEEL LIKE A WIZARD NOW!

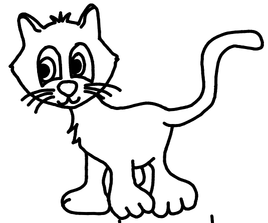
cast of characters

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

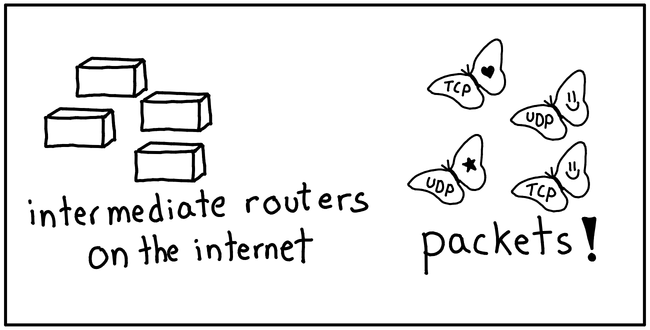
computers you'll talk to





the cat picture we're downloading

in the middle



♡ 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"`)

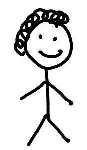
② How many packets were exchanged with metafilter.com's server?
(hint: search `ip.dst == 54.1.2.3`) put the IP from "ping metafilter.com" here

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



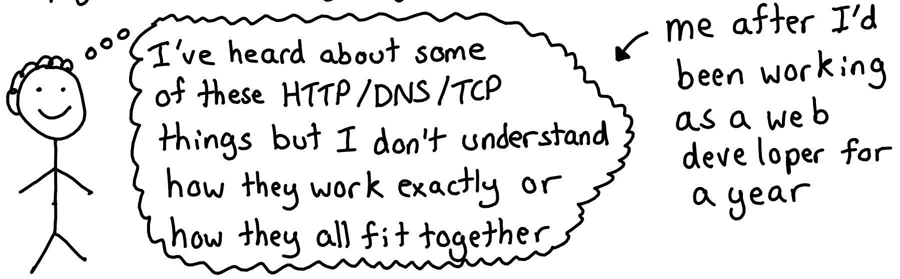
twitter: @b0rk
blog: http://jvns.ca

I put a picture of a cat on the internet here:

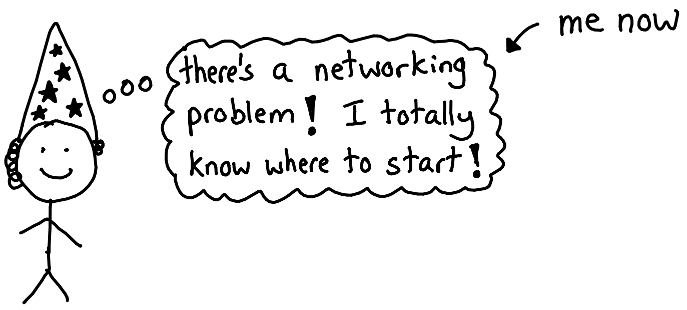
☆ jvns.ca/cat.png ☆ (go look!)

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)

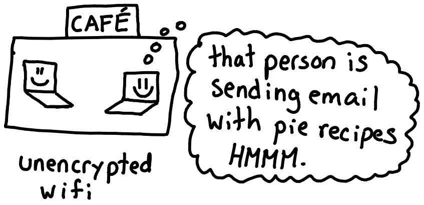
m	a	n	g
o	t	e	a

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.



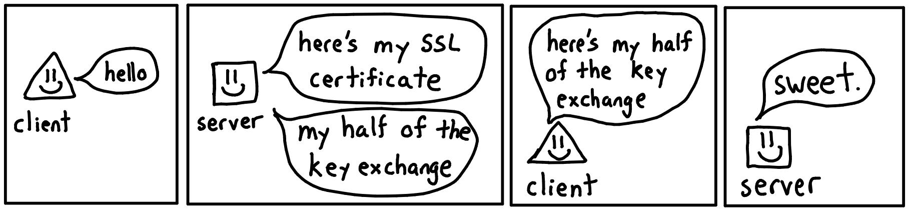
SSL encrypts your packets:

old packet	IP address + port stay the same ⟹	new packet
to: 9.9.32.94:443 from: 31.97.1.2:999		to: 9.9.32.94:443 from: 31.97.1.2:999
here is my secret lemon pie recipe	⟹	x8;´fae94aex jjb43,8b"5jkk

443 is the usual SSL port

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

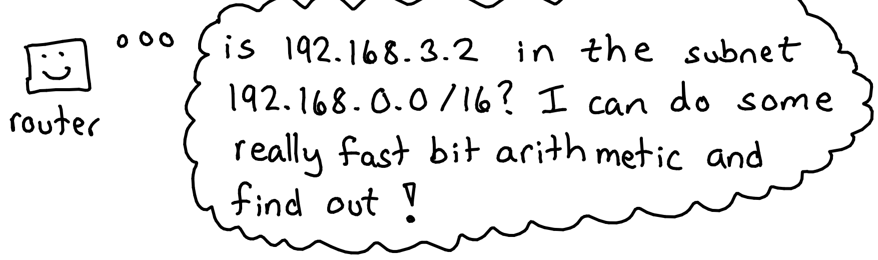
CIDR	range of IPs
10.0.0.0/8	10.*.*.*
10.9.0.0/16	10.9.*.*
10.9.8.0/24	10.9.8.*

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:

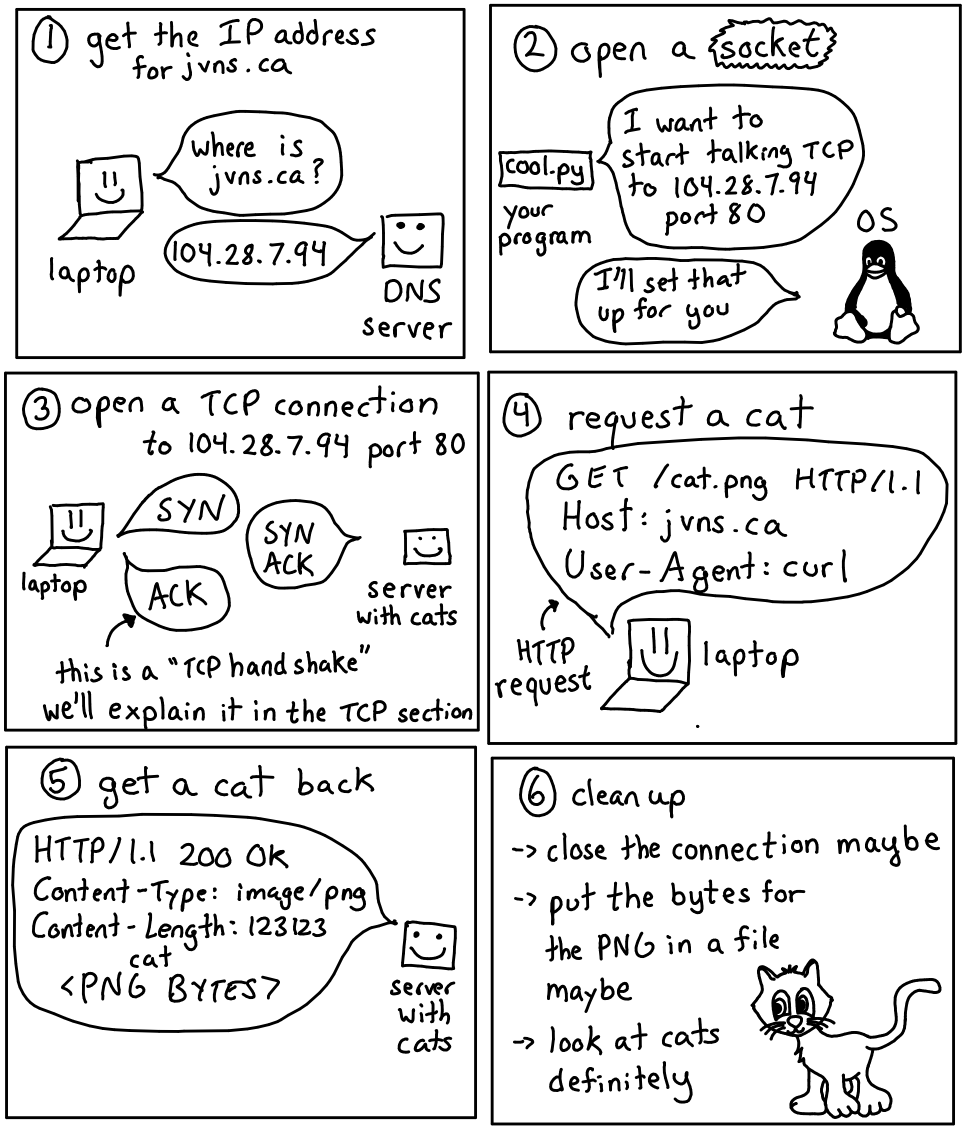
$$\underbrace{00001010\ 00001001\ 00000000}_{\text{first 24 bits}}\ 00000000$$

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.

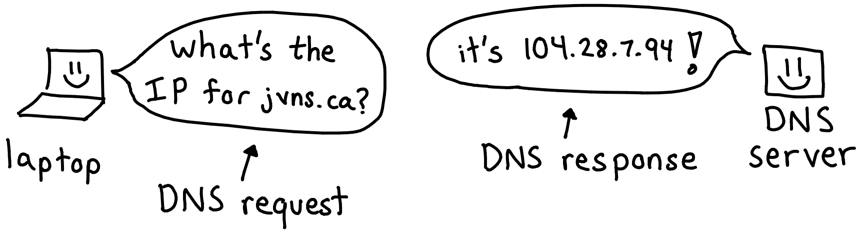


DNS

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

All networking happens by sending packets. 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.



The DNS request + response are both usually UDP packets.

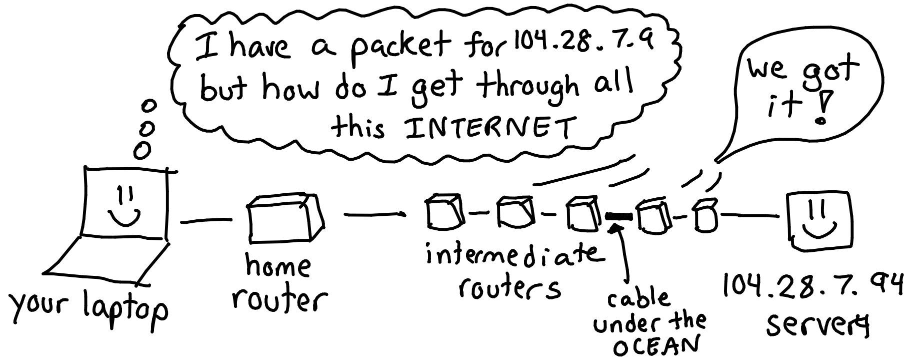
When you run `$ curl jvns.ca/cat.png` :

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

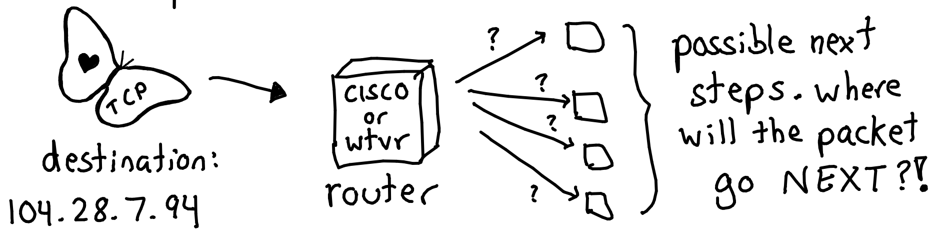
Your system's default DNS server is often configured in /etc/resolv.conf.

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

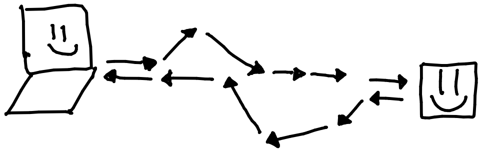


When a packet arrives at a router



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

A packet can take a lot of different routes to get to the same destination!



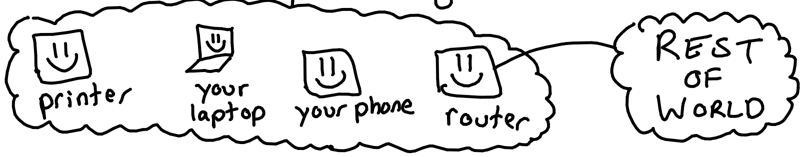
The route it takes to get from A->B might be different from B->A.

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

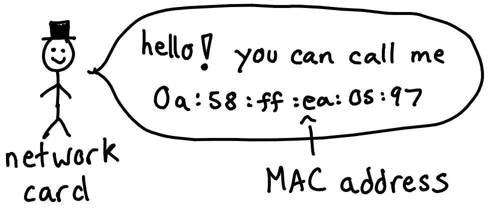
Local networking

how to talk to a computer in the same room

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

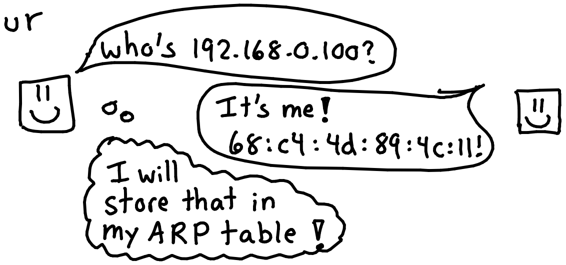


What does it mean to talk "directly" to another computer? Well, every computer on the internet has a network card with a MAC address.



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!

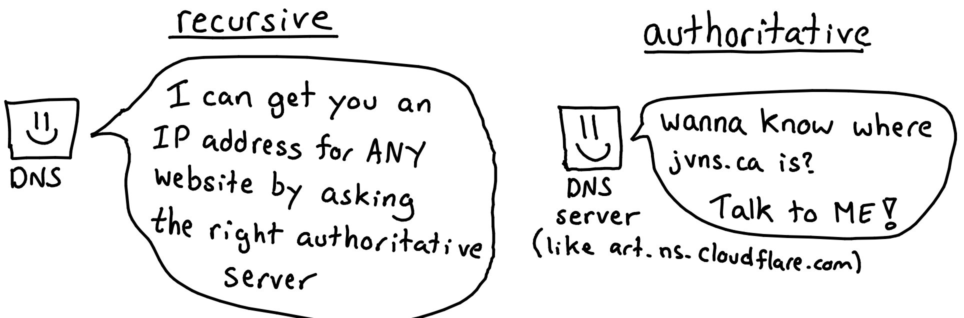
You can run arp -na to see the contents of the ARP table on your computer. It should look like this:

MAC for 192.168.1.120 (my printer)

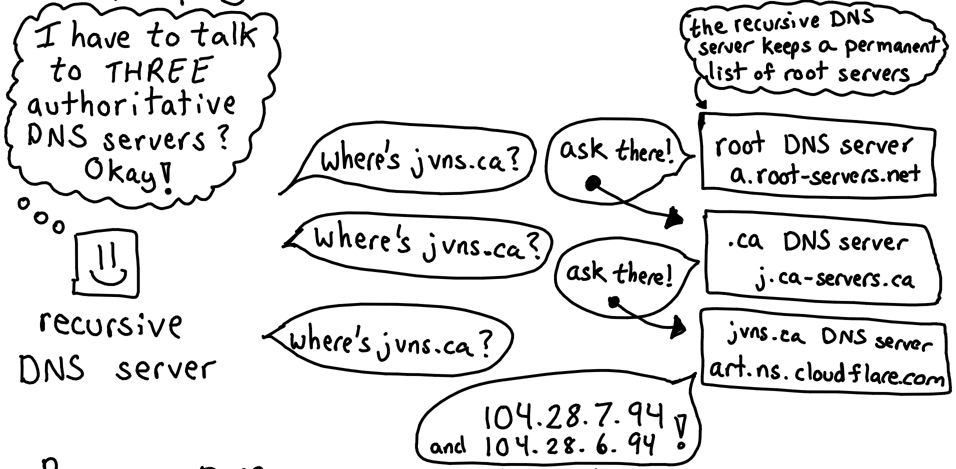
```
$ arp -na
? (192.168.1.120) at 94:53:30:91:98:c8 [ether] on wlp3s0
```

my wifi card

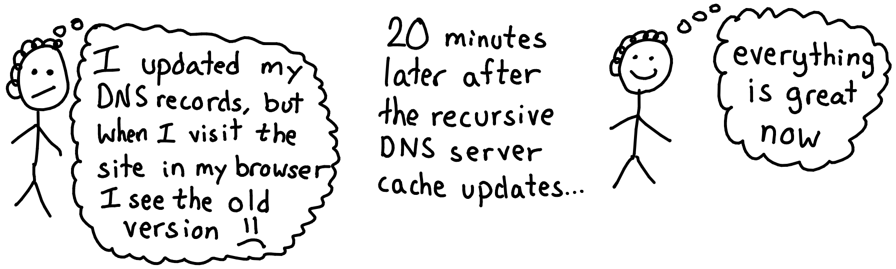
There are 2 kinds of DNS servers:


recursive
authoritative
DNS
I can get you an IP address for ANY website by asking the right authoritative server
DNS server
(like art.ns.cloudflare.com)
wanna know where jvns.ca is? Talk to ME!

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

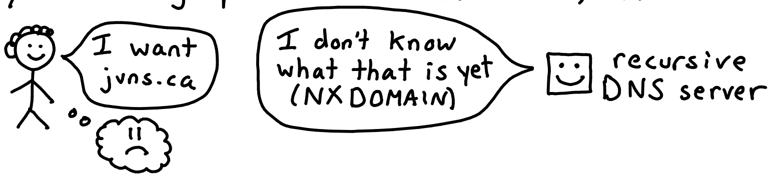

I have to talk to THREE authoritative DNS servers? Okay!
recursive DNS server
the recursive DNS server keeps a permanent list of root servers
where's jvns.ca?
ask there!
root DNS server a.root-servers.net
where's jvns.ca?
ask there!
.ca DNS server j.ca-servers.ca
where's jvns.ca?
jvns.ca DNS server art.ns.cloudflare.com
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



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:

UDP header

~ IP stuff ~

source port	destination port
length	UDP checksum

~ packet contents ~

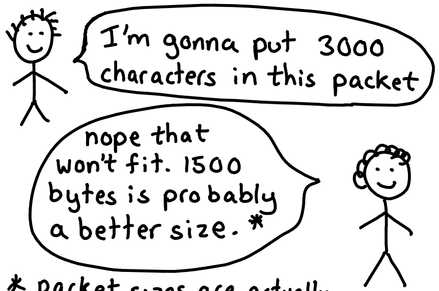
"unreliable data protocol" (not what it really stands for)

When you send UDP packets, they might arrive

- out of order
- never

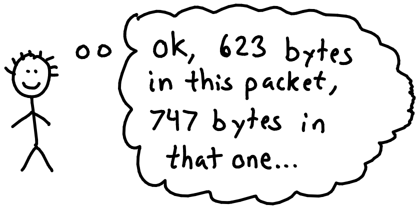
any packet can actually get last, but UDP won't do anything to help you.

Packet sizes are limited

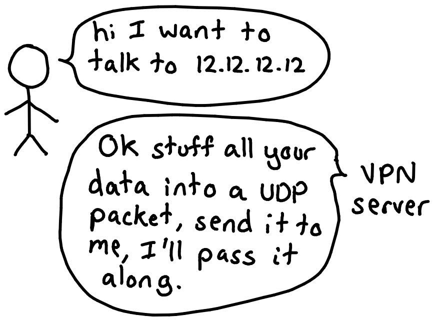

I'm gonna put 3000 characters in this packet
nope that won't fit. 1500 bytes is probably a better size. *

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

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



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

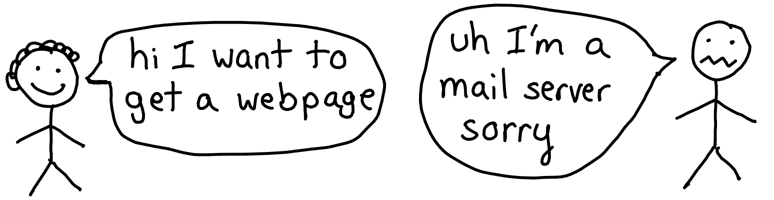
Read http://hpbn.co/webrtc for a GREAT discussion of using UDP in a real time protocol.

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:



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

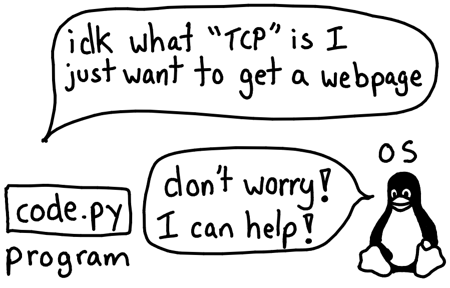
Some common ports:

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



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

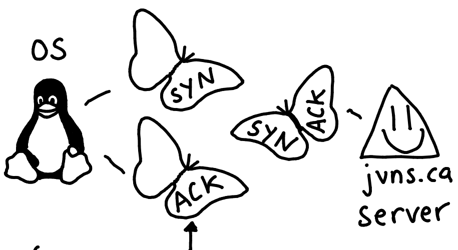
TCP — to use TCP

UDP — to use UDP

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

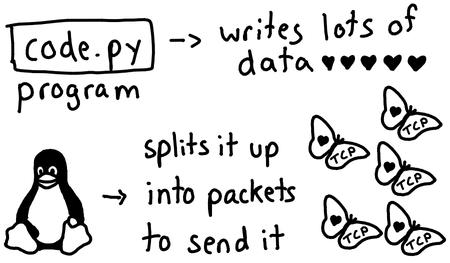
unix — to talk to programs on the same computer

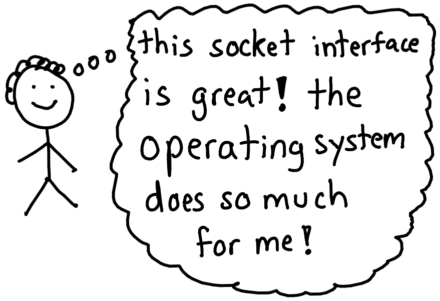
when you connect with a TCP socket



(we'll explain this SYN ACK thing soon)

when you write to a socket

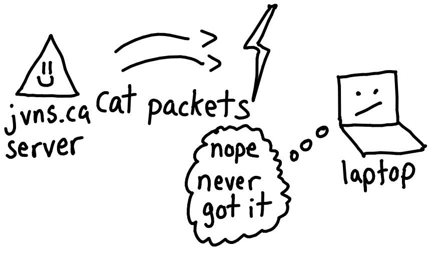

code.py
program
-> writes lots of data ♥♥♥♥♥
→ splits it up into packets to send it
TCP
TCP
TCP
TCP
TCP
TCP


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

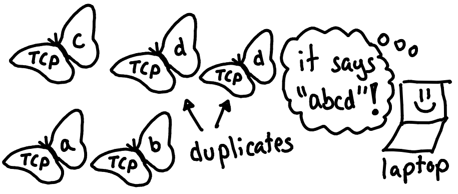
TCP: how to reliably get a cat

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.



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



how does TCP work, you ask? WELL!

how to know what order the packets should go in:

Every packet says what range of bytes it has

Like this:

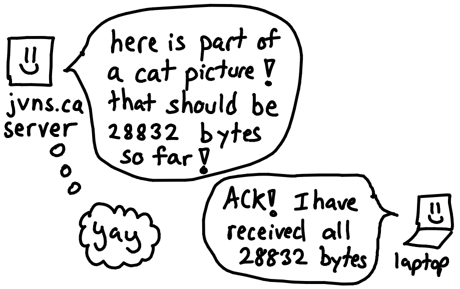
once upon a ti ← bytes 0-13
agical oyster ← bytes 30-42
me there was a m ← bytes 14-29

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"

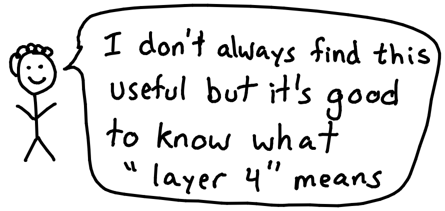
how to deal with lost packets:

When you get TCP data, you have to acknowledge 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 retry 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

112 bits
14 bytes

destination MAC	source MAC addr	type

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

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.

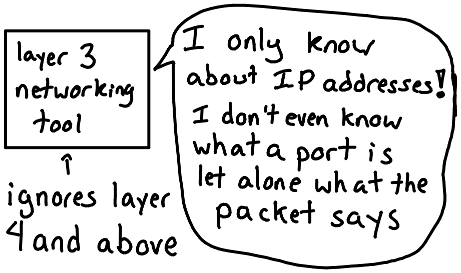
source port	destination port
length	UDP checksum

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

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

G	E	T	
/		H	T

← 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

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

Your home router looks at layers 2+3+4

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

The network card in your computer only cares about layers 1+2.

... 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:

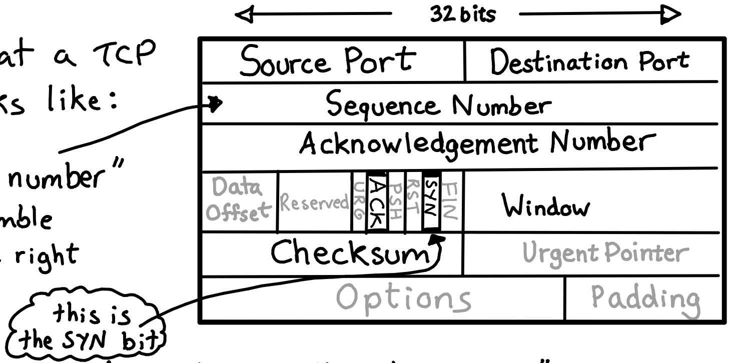
- what a **port** actually is
- how a **packet** is put together
- security: how SSL works
- the different **networking layers**
- UDP and why it's amazing

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**

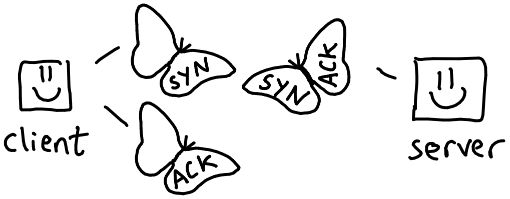
The TCP Handshake

This is what a TCP header looks like:



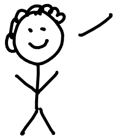
the "sequence number" lets you assemble packets in the right order ⩌

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



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

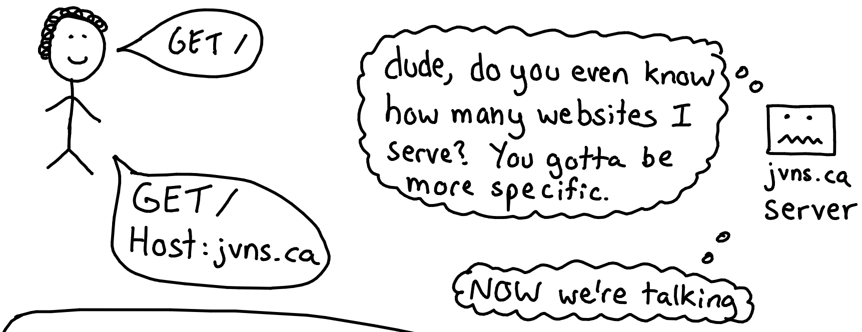
This is a HTTP request:

```
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.