Network Fundamentals

From Zero to HTTP

One To One

- Two machines can talk to each other
- Each machine has a network interface
- Network interfaces can be connected directly to each other via network cable
- Each network interface has a Media Access Control (MAC) address (AKA hardware address)
- MAC addresses look like this: 50:46:5d:54:94:23
- MAC addresses are globally unique (at least in theory)
- Data is sent in chunks called ‘frames’
- Each frame has a source and destination MAC address

How Do They Know The Destination MAC Address?

- They don't!
- They *do* know the *IP address* though (because you tell them it)
- An IPv4 address looks like this: 192.168.0.1
  - There's IPv6 too, but we won't be covering it here
- A machine can ask the whole network who has a particular IP
- Machines ignore frames that don't have their MAC as the destination
- But there's a special 'anyone' or 'broadcast' MAC: ff:ff:ff:ff:ff:ff

Getting Your Network Interface Info

▶️ **ifconfig enp3s0**

```
enp3s0    Link encap:Ethernet  HWaddr 50:46:5d:54:94:23
          inet addr:192.168.1.30  Bcast:192.168.1.255  Mask:255.255.255.0
          inet6 addr: fe80::5246:5dff:fe54:9423/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:48241295 errors:0 dropped:0 overruns:0 frame:0
          TX packets:24083899 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:49741929087 (49.7 GB)  TX bytes:2925004440 (2.9 GB)
```

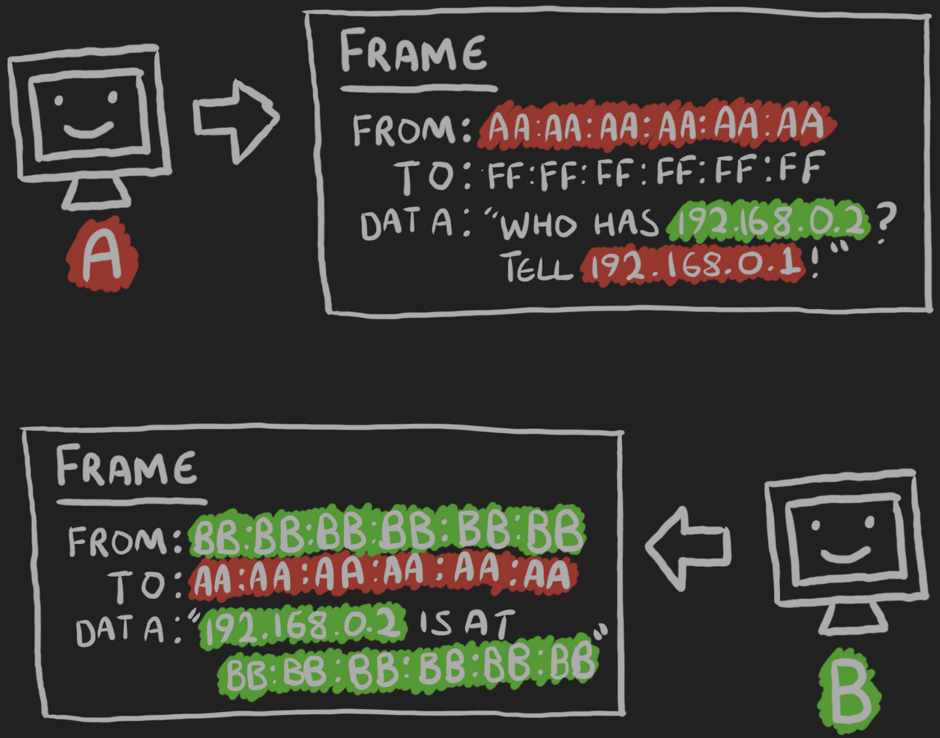
▶️ **ip a show dev enp3s0**

```
2: enp3s0: <BROADCAST,MULTICAST,UP,LOWER_UP> mtu 1500 qdisc pfifo_fast state UP group default qlen 1000
    link/ether 50:46:5d:54:94:23 brd ff:ff:ff:ff:ff:ff
    inet 192.168.1.30/24 brd 192.168.1.255 scope global enp3s0
       valid_lft forever preferred_lft forever
    inet6 fe80::5246:5dff:fe54:9423/64 scope link
       valid_lft forever preferred_lft forever
```

Is Anybody There?

- Machine A wants to talk to Machine B
- Machine A has IP 192.168.0.1 and MAC aa:aa:aa:aa:aa:aa
- Machine B has IP 192.168.0.2 and MAC bb:bb:bb:bb:bb:bb
- Machine A sends a frame like this:
  - Source MAC: aa:aa:aa:aa:aa:aa
  - Destination MAC: ff:ff:ff:ff:ff:ff
  - Data: “Who has 192.168.0.2? Tell 192.168.0.1!”
- Machine B responds with a frame like this:
  - Source MAC: bb:bb:bb:bb:bb:bb
  - Destination MAC: aa:aa:aa:aa:aa:aa
  - Data: “192.168.0.2 is at bb:bb:bb:bb:bb:bb!”
- Both machines store the IPs and corresponding MACs in their Address Resolution Protocol (ARP) cache for future use

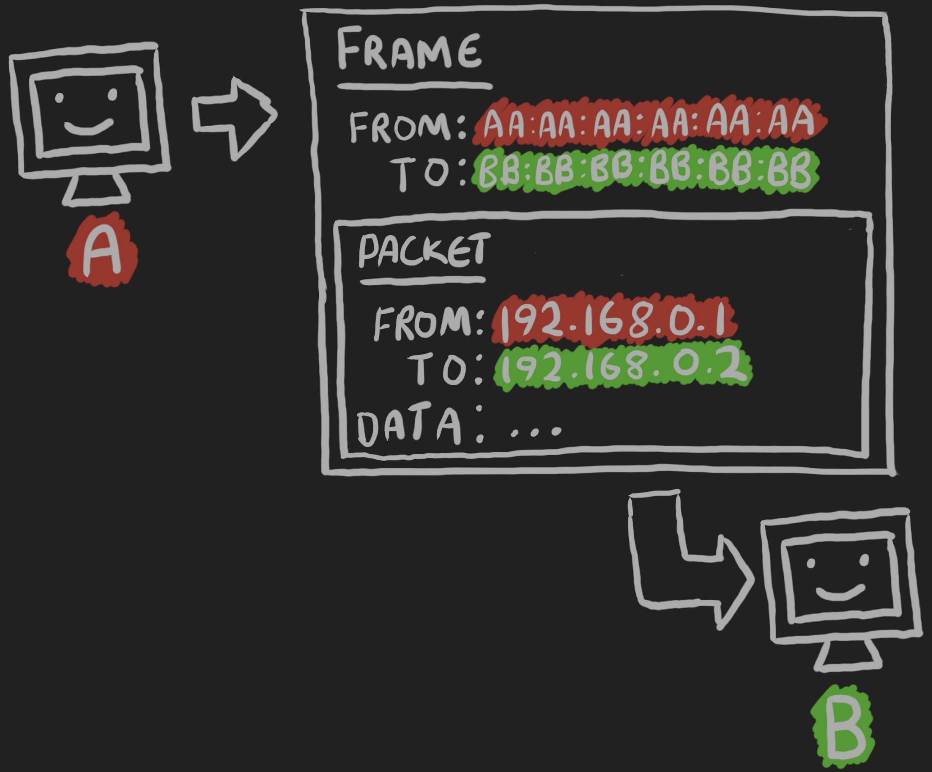
Address Resolution Protocol



The Next Message

- Machine A wants to talk to Machine B again
- This time Machine A can find the MAC address in its ARP cache
- Machine A sends a frame that looks like this:
  - Source MAC: aa:aa:aa:aa:aa:aa
  - Destination MAC: bb:bb:bb:bb:bb:bb
  - Data: …
- Inside the data is an IP ‘packet’, which looks like this:
  - Source IP: 192.168.0.1
  - Destination IP: 192.168.0.2
  - Data: …
- The data in the last slide was actually an ARP Packet
- Why a MAC *and* an IP?
  - Machines can have more than one IP address… And other reasons too

The ARP Cache



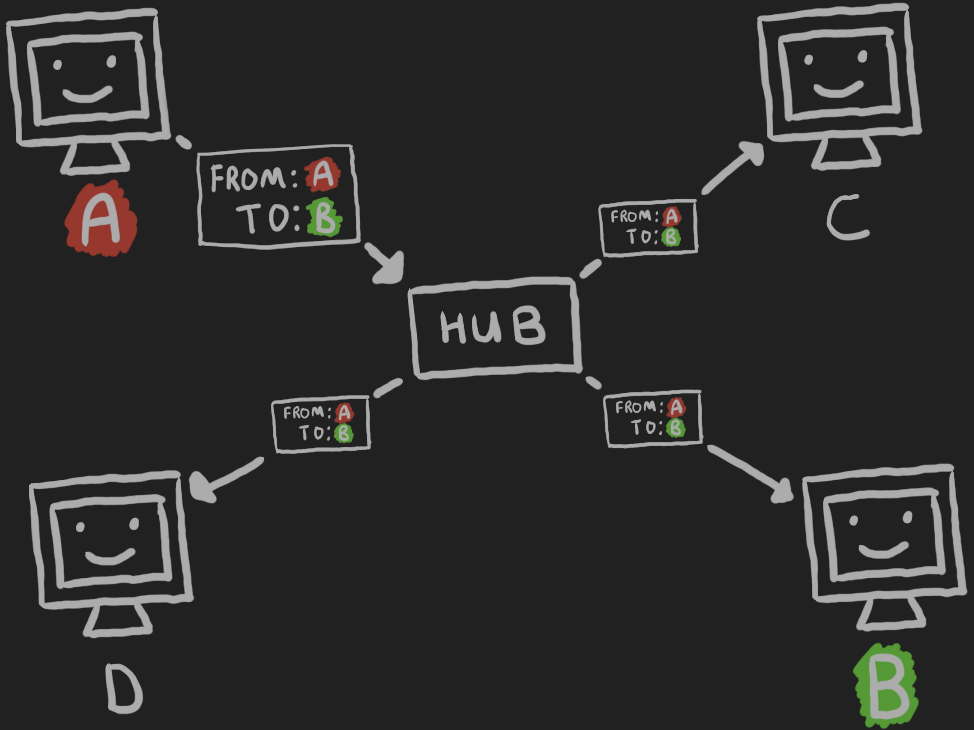
Seeing Your ARP Cache

```
▶️ ip n
192.168.1.170 dev enp3s0 lladdr 00:17:88:49:a0:62 STALE
192.168.1.138 dev enp3s0 lladdr 94:44:44:ed:f5:c8 STALE
192.168.1.114 dev enp3s0 lladdr f4:5c:89:c1:ed:5f STALE
192.168.1.60  dev enp3s0 lladdr 00:18:a9:74:a5:88 STALE
192.168.1.1   dev enp3s0 lladdr 98:fc:11:85:74:6c REACHABLE
192.168.1.179 dev enp3s0 lladdr dc:3a:5e:5d:e0:9d STALE
192.168.1.163 dev enp3s0 lladdr 70:48:0f:c9:19:42 STALE
192.168.1.23  dev enp3s0 lladdr 38:ea:a7:a9:34:f3 STALE
192.168.1.134 dev enp3s0 lladdr 8c:f5:a3:30:af:a7 STALE
192.168.1.10  dev enp3s0 lladdr 44:d9:e7:62:ab:cc REACHABLE
```

More Than Two Machines

- More than two machines can be connected to a *hub*
- A hub is pretty dumb
- It just sends everything it receives back out to all ports
- Machines ignore frames not intended for them so everything is (mostly) fine
- Everything that worked for two machines works exactly the same way
- But:
  - It's slow (10Mbit, 100Mbit if you're lucky)
  - You get *collisions* (machines trying to talk over each other)
  - We can do better

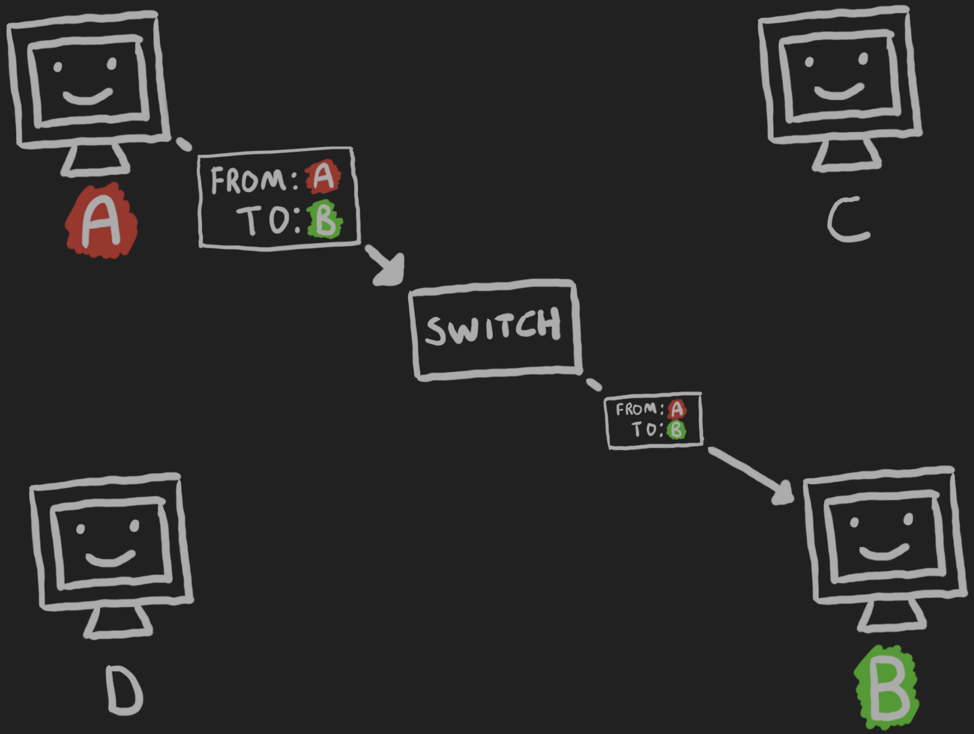
Hubs



Switching

- Network *switches* are smarter and more efficient
- Switches remember the source MACs they have seen on each port
- Frames are only sent to the port that a MAC is connected to
- If the switch doesn't know where a MAC is: it sends to all ports
    - It never knows where ff:ff:ff:ff:ff:ff is so that always goes to all ports!
- Fewer collisions!
- Much faster!
    - 10Gbit is fairly common in switched networks

Switches



Subnets

- Machines can only directly send IP packets to machines on the same network
- Sooo… How do we define what a network (technically a sub-network) is?
- As well as an IP, each machine has a *subnet mask*
  - They look like this: 255.255.255.0
- The subnet mask is used in combination with a source and destination IP to decide if they are on the same subnet or not
- It's actually much easier to understand in binary!

Subnet Masks

- Two machines are on the same subnet if the bits in their IPs match where the corresponding bit in the subnet mask is a 1

These two are on the *same* subnet:

```
Source:       192.168.0.1     11000000.10101000.00000000.00000001
Destination:  192.168.0.2     11000000.10101000.00000000.00000010
Subnet Mask:  255.255.255.0   11111111.11111111.11111111.00000000
```

These two are on *different* subnets:

```
Source:       192.168.0.1     11000000.10101000.00000000.00000001
Destination:  192.168.31.2    11000000.10101000.00011111.00000010
Subnet Mask:  255.255.255.0   11111111.11111111.11111111.00000000
```

CIDR Notation

- It gets a little tiresome specifying the IP *and* the subnet mask
- You can use *Classless Inter-Domain Routing* notation instead
- Count the number of 1s in the subnet mask!

```
10.0.0.1/255.255.255.0

00001010.00000000.00000000.00000001/11111111.11111111.11111111.00000000

10.0.0.1/24
```

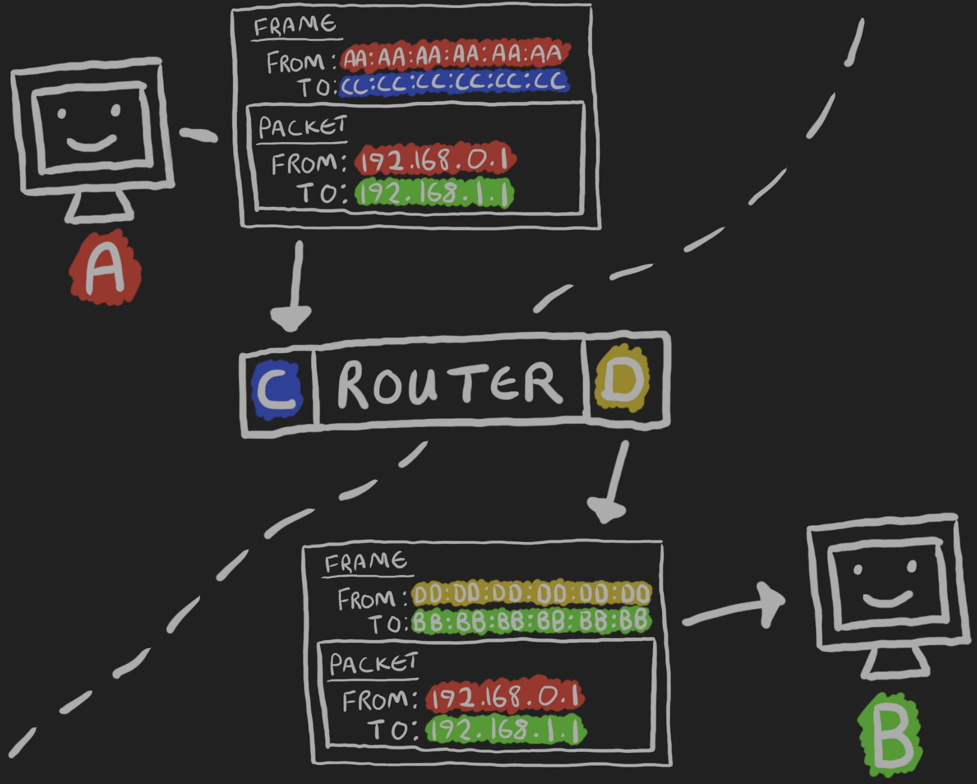
Routing

- To send a packet to a machine on another subnet the frame is sent to a *router*
- A router *usually* has more than one network interface (and MAC address)
- A router *always* has more than one IP address (at least one per subnet)
- Machine A (subnet one):
  - MAC: aa:aa:aa:aa:aa:aa
  - IP: 192.168.0.1 / 255.255.255.0
- Machine B (subnet two):
  - MAC: bb:bb:bb:bb:bb:bb
  - IP: 192.168.1.1 / 255.255.255.0
- Router (both subnets):
  - MAC1: cc:cc:cc:cc:cc:cc
  - IP1: 192.168.0.254 / 255.255.255.0
  - MAC2: dd:dd:dd:dd:dd:dd
  - IP2: 192.168.1.254 / 255.255.255.0

An Example Hop

- Machine A wants to talk to machine B, but machine B is on a different subnet
- So it sends a frame using the MAC for its *default gateway* as the destination:
  - Source MAC: aa:aa:aa:aa:aa:aa
  - Destination MAC: cc:cc:cc:cc:cc:cc (the router's first MAC!)
  - Source IP: 192.168.0.1
  - Destination IP: 192.168.1.1 (machine B's IP!)
- Router receives the frame, and then sends:
  - Source MAC: dd:dd:dd:dd:dd:dd (the router's second MAC)
  - Destination MAC: bb:bb:bb:bb:bb:bb
  - Source IP: 192.168.0.1
  - Destination IP: 192.168.1.1
- The router modified the source and destination MACs
- Machine B receives the frame from the router :)

A Hop


FRAME
FROM: AA:AA:AA:AA:AA:AA
TO: CC:CC:CC:CC:CC:CC
PACKET
FROM: 192.168.0.1
TO: 192.168.1.1
A
C
ROUTER
D
FRAME
FROM: DD:DD:DD:DD:DD:DD
TO: BB:BB:BB:BB:BB:BB
PACKET
FROM: 192.168.0.1
TO: 192.168.1.1
B

Multiple Choice

- Machine A sent the frame to its default gateway as a last resort
- It might have had another option in its *routing table*:

Network	Subnet Mask	Gateway
0.0.0.0	0.0.0.0	192.168.0.254
192.168.1.0	255.255.255.0	192.168.0.253
192.168.2.0	255.255.255.0	192.168.0.252

- With this table the MAC for 192.168.0.253 would have been the destination
- Multiple networks connected via routers form what we call the internet :)

The OSI Model

#	Name	Unit	What?
7	Application	Data	HTTP, FTP etc
6	Presentation	Data	Encryption! TLS etc
5	Session	Data	PPTP, SOCKS
4	Transport	Segments	TCP, UDP
3	Network	Packets	IP and routing
2	Data-Link	Frames	MAC addresses and the like
1	Physical	Bits	Electricity on a wire

The Internet Protocol Suite

- An alternate, and much more simple model
- Still just a model; not everything is so well-defined

#	Name	Unit	What?
4	Application	Data	HTTP, FTP etc
3	Transport	Segments	TCP, UDP
2	Internet	Packets	IP and routing
1	Link	Frames	MAC addresses and the like

Transport Control

- So far we’ve concerned ourselves only with one-way communication
- The network is unreliable, but we need reliable communication
- How do you know if someone got your letter?
  - Ask them to send you one back!
  - If you don’t get a response after a while, send another letter :)
- TCP provides reliability for IP packets
- TCP adds *ports* so that we can have more than one conversation going on between two IPs
  - Ports are just numbers. You need a source port and a destination port
- If you don’t need the reliability that TCP provides you can use *UDP*

Let’s Talk TCP

Machine A		Machine B
Hey, can we talk?	→	...
...	←	Sure.
OK! Let’s talk!	→	...
So, can you do this thing for me?	→	...
...	←	Yes, I hear you.
...	←	Here’s the thing you wanted.
Got it!	→	...
...	←	I’m leaving.
Fine! Me too!	→	...
...	←	Good.

The Real Version

192.168.0.1:56789		192.168.0.2:80
SYN	→	...
...	←	SYN, ACK
ACK	→	...
DATA	→	...
...	←	ACK
...	←	DATA
ACK	→	...
...	←	FIN
FIN, ACK	→	...
...	←	ACK

Retransmissions

- If the sender doesn't receive an ACK after a while it will resend the data

192.168.0.1:56789		192.168.0.2:80
	...handshake...	
DATA	→	...
...	←	ACK
...	←	DATA
	...time passes...	
...	←	DATA
ACK	→	...
	...termination...	

Skipping A Few Layers (for OSI at least)

- HTTP is an *application layer* protocol
- HTTP version 1.1 is just plaintext
  - So simple you can write it by hand!
- It might be encrypted with, say, TLS, but we'll ignore that for now
- HTTP version 2 isn't plaintext, but we're going to ignore that too
- When we're talking about an application layer protocol we can (mostly) ignore the lower layers :)

Let’s Talk HTTP

192.168.0.1:56789		192.168.0.2:80
	...handshake...	
GET /index.html HTTP/1.1 Host: example.com Connection: close User-Agent: slidedeck/0.3 Accept: */*	→	...
...	←	HTTP/1.1 200 OK Content-Type: text/html Content-Length: 1337 <!doctype html> <html> ...
	...termination...	

The Request

- Each line in the request is separated by a Carriage Return and a Line Feed character (CRLF sequence)
- The request is terminated by two CRLF sequences
- *Headers* are sent in the form *Key: value*

What	What?
`GET /index.html HTTP/1.1`	Get me the file at /index.html; I’m using HTTP version 1.1
`Host: example.com`	The name of the host I’m connecting to is example.com
`Connection: close`	Please close the TCP connection when you’ve sent me the data
`User-Agent: slidedeck/0.3`	Just FYI, my client software is slidedeck 0.3
`Accept: */*`	I’ll accept any kind of data in response!

The Response

- The response headers are separated by CRLF sequences too
- The response *body* is separated from the headers by two CRLF sequences

What	What?
`HTTP/1.1 200 OK`	I'm using HTTP version 1.1; that request is OK!
`Content-Type: text/html`	I'm going to send you some text that happens to be HTML
`Content-Length: 1337`	You'll need to read 1337 bytes to get all of the response body

`<!doctype html>`
`<html>`
`...`
	The response body

What’s Your Name?

- We’ve been talking about IP addresses this whole time
- It’s easier to remember ‘example.com’ instead of ‘93.184.216.34’
    - And a *lot* easier than remembering ‘2606:2800:220:1:248:1893:25c8:1946’ :)
- The Domain Name System (DNS) translates names into IP addresses
- DNS uses UDP (most of the time)
- It usually listens on port 53
- Clients request *records* from DNS servers

Record Types (a non-exhaustive list)

- There's several different kinds of DNS record; each with a different purpose
- Each record is stored against a *name* like 'example.com'

Type	Example	What?
A	`93.184.216.34`	An IPv4 Address
AAAA	`2606:2800:220:1:248:1893:25c8:1946`	An IPv6 Address
CNAME	`origin.example.com`	An alias for another name
MX	`mail.example.com`	A mail exchange handler
NS	`ns1.webhost.com`	An authoritative nameserver
TXT	`Clacks-Overhead=GNU Terry Pratchett`	Some human-readable text

An Example Lookup

- DNS queries use UDP, so there's no handshake
- That also means it could be difficult to correlate requests and responses
- The response includes the query so the client knows what it's a response to
- The request and response aren't actually plaintext, but binary is hard to read in examples

192.168.0.1:56789		8.8.8.8:53
`Query: A example.com`	→	…
…	←	`Query:  A example.com` `Answer: A 93.184.216.34`

CNAMEs

- We need an IP address to make a connection to a host
- If there's no A record for the name, but there is a CNAME record, the DNS server will respond with the CNAME record, and the A record for that name if one exists

192.168.0.1:56789		8.8.8.8:53
`Query: A example.com`	→	…

…	←	`Query: A example.com`
		`Answer: CNAME origin.example.com`
		`Answer: CNAME webserver.example.com`
		`Answer: A 93.184.216.34`

Load Balancers

- One server is rarely enough to handle all of your traffic
- Load Balancers split incoming requests between multiple servers
- Some load balancers work at the Transport Layer (TCP etc)
- Others work at the Application Layer (HTTP etc)
- Transport Layer is ‘easier’ (i.e. requires less CPU time)
- Application Layer is more powerful
  - You can send requests to, say, a particular HTTP endpoint to a different pool of servers
  - You can respond to some requests without hitting a backend server at all
- Both kinds have multiple load balancing algorithms
  - Round Robin / Weighted Round Robin
  - Least Connections
  - Hashed on some property of the connection (e.g. source IP)
  - Random

Transport Layer Load Balancers

- All packets for a TCP session are sent to and from the same backend server
- Works for any backend service that uses TCP
  - That covers the vast majority of backend services
    - Web Servers
    - Database Servers
    - Internet-enabled Toasters
- Can work for UDP too, but the application layer protocol on top must be stateless and/or you must use a hash-based load balancing algorithm
- No need to decrypt traffic in transit
- Requests can be split based only on Transport or Internet/Network level details like source IP address
- Generally fairly limited in their capabilities

Application Layer Load Balancers

- They actually understand the application layer protocol (e.g. HTTP)
- That lets you do useful stuff like:
  - Split requests based on application layer details (e.g. HTTP path, query string, cookies)
  - Respond to some requests without hitting a backend server (e.g. redirecting HTTP to HTTPS)
  - Edge Side Includes (i.e. calling more than one backend server to form one response)
  - Block requests you suspect are malicious (e.g. HTTP request contains possible XSS payload)
- Takes a lot more processing power to run
- Usually made for only one protocol (e.g. an HTTP load balancer couldn’t really do anything with MySQL connections)
- If you’re using an encrypted transport like TLS the load balancer must decrypt incoming traffic before it can be processed
  - That means you’ve got to deploy your private keys to your load balancers
  - Sometimes you might need to re-encrypt afterwards (e.g. for cardholder data)

Network Address Translation (NAT)

- IPv4 space is limited - IPv4 addresses are 32 bit unsigned integers
- Max addresses: 4,294,967,295
- Subtracting the reserved ranges it's actually only 3,702,258,430
- More than 7,607,000,000 people on earth as of March 2018
- How many internet connected devices do *you* own?
  - There was more than 30 devices on my home network last time I checked
- NAT is *a* solution to the IPv4 space problem, but also a good way to make sure your network really is private too
  - E.g. private addresses can't be routed to from the public internet unless you explicitly allow it

An Aside: Reserved IPv4 Space

- Private-use Ranges:
  - 10.0.0.0/8
  - 172.16.0.0/12
  - 192.168.0.0/16
- Local / loopback:
  - 127.0.0.0/8
  - 0.0.0.0/8
- And 10 or so more ranges reserved for a bunch of different reasons
  - E.g. documentation, broadcast ranges, ‘future use’

How To NAT

- Machine A (192.168.0.10) is on your network, behind NAT
- It wants to connect to Google's DNS servers (8.8.8.8 port 53)
- Machine A sends a packet:
  - Source MAC: aa:aa:aa:aa:aa:aa
  - Dest MAC: cc:cc:cc:cc:cc:cc (the internal interface on the default gateway)
  - Source IP/port: 192.168.0.10:34567 (Machine A's IP)
  - Dest IP/port: 8.8.8.8:53
- The default gateway receives the packet and rewrites the source IP/port before sending it on:
  - Source IP/port: 62.52.42.32:45678 (The gateway's public IP)
  - Dest IP/port: 8.8.8.8:53
- The translation is recorded so that return traffic can have its *destination* IP and port translated