CS314 2010 23/24

IPv4: Internet Protocol version 4

- Concept
- Addressing
- Packet format
- Fragmentation
- Control messages (ICMP)
- Getting an address (DHCP)
- Finding neighbours (ARP)
- Naming things (DNS)

Concept of a connectionless datagram (1)

- The idea goes back to 1962, and the current version of IP was defined in the late 1970s
- Share expensive links by mixing variable-length packets sent between logical addresses
  - Much more dynamic than hardware multiplexing or circuit switching
  - As we've seen, allows a variety of routing mechanisms

Concept of a connectionless datagram (2)

- *Share expensive links by mixing variable-length packets sent between logical addresses*
  - Advantages: sharing costs, universal connectivity, great flexibility
  - Disadvantages: variable response time, risk of congestion or packet loss
- The success of the Internet shows that the advantages far outweigh the disadvantages

Logical addressing

- The source and destination addresses of IP packets are logical, not physical
  - Assigned by software
    - and can be changed
  - Assigned to interfaces (not whole computers)
  - Must be unique, for routing to be possible
  - Must be related to topology, for routing to *scale*
  - Are also used as unique identifiers, as we'll see later
  - One interface can have multiple addresses (rare in IPv4)

IPv4 Address Format

- In the abstract, it's just a 32 bit binary number:
  `01010011 11001010 10010110 00000010`
- Conventionally written in “dotted decimal:”
  `83.202.150.2`
- Upper layers of software have no business treating addresses as anything but meaningless bit strings
- But to the routing system, addresses have some real meaning

Location versus Identity

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         IPv4 Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

<----- high order bits indicate    |  low order bits indicate --->
       location for routing        |  identity on the LAN
                                   |
                             NO FIXED BOUNDARY
```

- For example, in 10.1.2.17, you cannot assume that the network is 10.1.2.0/24
  - i.e. a subnet with 256 addresses
- It might equally well be, e.g., 10.1.2.16/28
  - i.e. a subnet with 16 addresses

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 1|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Old-fashioned IPv4 addressing (1)

- In the early years of IPv4 (up to about 1993), addresses were divided into three *classes*
  - Class A, user site was given a /8 prefix and had 24 bits free to assign locally (16M addresses)
  - Class B, /16 prefix with 16 local bits (65k addresses)
  - Class C, /24 prefix with 8 local bits (256 addresses)
- This was scrapped because it led to inefficient use of address space and to sparse routing tables

Old-fashioned IPv4 addressing (2)

- Addresses are now assigned in very large blocks to ISPs and sub-divided among their customers
  - CIDR (classless inter-domain routing) was in fact brought in together with BGP4
  - Because of CIDR, you can't tell how long the prefix is by looking at the address
  - Instead (e.g. in RIPv2 packets) you specify the complete prefix, e.g. 130.216.32.0/24

Special types of IPv4 address (1)

- So far we have discussed *unicast* addresses
  - That means an address used to send a packet to exactly one interface
- IP also supports *multicast* addressing and routing
  - That means an address used to send a packet to a large set of interfaces in parallel
  - Multicast IPv4 addresses are under prefix 224/4:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 0 x x x x x x x x x x x x x x x x x x x x x x x x x x x x|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- The *broadcast* address is 255.255.255.255 but it only works locally (it's blocked by routers)

Special types of IPv4 address (2)

- Sometimes a unicast address is used as an *anycast* address
  - Used to send a packet to a group of interfaces, but only one should respond, normally to provide redundant servers
  - There is no way to tell an anycast address by looking at it; they have to be manually coded into the routing system
- 0.0.0.0 means “this host”
  - “host” is internet jargon for “computer”
  - 0.0.0.0/0 is also the way a default route is identified
- 127.0.0.1 is the loopback address (send packets to yourself)
- 169.254.0.0/16 is “link local” space for isolated networks

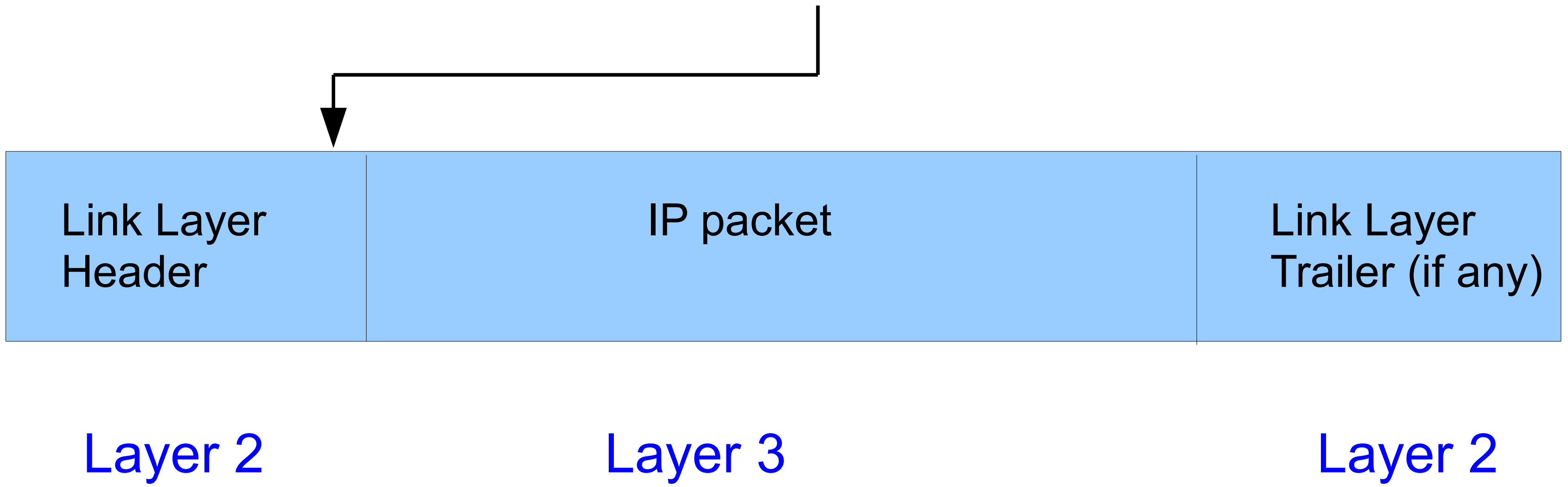
  (RFC 3927)

Special types of IPv4 address (3)

- Three address ranges are reserved for private use *within* a site
  - 10.0.0.0/8
  - 172.16.0.0/12
  - 192.168.0.0/16
- Since *anybody* can use these addresses, they are ambiguous and must *never* be routed off-site
- (This is not a complete list of special addresses. For a complete list, see RFC 3330 at www.rfc-editor.org)

Mapping to Layer 2

- The IP packet has to be sent inside a Layer 2 frame, such as an Ethernet frame
- The exact way this is done depends on the type of Layer 2 link
  - e.g. using Ethertype 0x0800 on Ethernet



IPv4 Packet Format

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Version|  IHL  |  DS Field     |          Total Length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Identification        |Flags|      Fragment Offset    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time To Live |    Protocol   |         Header Checksum       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Source Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Payload...                                 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                     ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    ...end of Payload          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Explanation of IPv4 header (1)

- Version: 4
- IHL (IP header length)
  - header length (bytes/4, i.e. 32 bit words)
- DS (differentiated services) Field, previously known as TOS (type of service) Field
  - 8 bits used to manage quality of service
- Total Length
  - length of IP header plus IP payload (bytes)
- Identification, Flags and Fragment Offset
  - used for packet fragmentation, see later

Explanation of IPv4 header (2)

- Time To Live (often called TTL)
  - actually a hop count, decreased by 1 at each router. The packet is discarded if TTL=0, to prevent loops
- Protocol
  - a value that defines the type of payload (TCP, UDP, etc.)
- Header checksum
  - 16 bit 1's complement of 16 bit 1's complement sum of all other header fields
  - recalculated by each router, since TTL changes
- Source and Destination addresses
  - as defined previously

IPv4 Header Options

- Most packets don't have them
  - New options are hard to deploy since old routers don't like them
- All options start with an option type byte

```
+--------+
|CxxNNNNN|
+--------+
```

  - C = 1 copied into each fragment, in case of fragmentation
  - C = 0 not copied
  - xx = option class (control or debugging)
  - NNNNN = option number
- Most options have more bytes

```
+--------+--------+--------+      -+
|CxxNNNNN| size   | data...|  ...  |
+--------+--------+--------+      -+
```

Example IPv4 Header Options

- Record Route
  - each router inserts its address in the option
  - generally blocked due to security worries
- Loose Source Route
  - allows the sender to specify the route
  - also performs 'record route'
  - generally blocked due to security worries
- Router Alert
  - tells each router to check further into the packet instead of just forwarding it
  - a good way to slow your packet down
- Generally speaking, header options were not a big success in the IPv4 design

Fragmentation

- An IPv4 host is required to handle datagrams of at least 576 bytes including the IPv4 header
- A given network path has a Maximum Transmission Unit (MTU) size, normally more than 576
  - Somewhat less than Ethernet size is common, 1400-1500 bytes
  - Fragmentation is designed to work for link MTUs down to 68 bytes
- Two problems to send a packet > link MTU size
  1. How to know what the MTU size is?
  2. How to split the large packet up?
- For the moment, assume we know the MTU size
- The hard part isn't fragmentation; it's re-assembly

The fragment header

- The sender splits up the packet; each fragment has a fragment header:

```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Identification        |Flags|      Fragment Offset    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

  - Identification: all fragments of the same packet have the same value
  - Flags
    - one unused bit
    - DF bit - if set, Don't Fragment this packet
    - MF bit - if set, More Fragments will follow
  - Fragment offset: how far into the packet this fragment begins, in units of 8 bytes
- If a sender (usually a router) knows that the next hop MTU is too small, it splits the packet into fragments

Reassembling fragments

- Routers don't reassemble fragments; that's left to the final receiver
- If you receive a packet with an unknown non-zero Identification value, you must
  - reserve a reassembly buffer
  - tag the buffer with the Identification value
  - store the fragment in the buffer at the given offset (remembering that the first fragment may not arrive first and the last fragment may not arrive last)
  - as further fragments with the same Identification arrive, store them in the buffer
  - when all fragments have arrived, act as if the whole packet had just arrived
  - if not all fragments arrive after a timeout, discard the buffer

Problems with fragmentation

- Double fragmentation
  - if MTU reduces twice along the path, fragmentation could happen twice
- Silly fragmentation
  - if the actual MTU is just a bit shorter than each packet we'll keep sending one long fragment and one very small one
- Reassembly is a slow process
- Interferes with TCP flow control
- On gigabit networks, the 16 bit ID field can wrap around ('recycle') in less time than the reassembly timeout
  - disastrous, as fragments of a new packet may be mistaken for lost fragments of an old one

ICMP: Internet Control Message Protocol

- Used for low-level management functions in an IP network
- Sent as IP packets with Protocol = 1
- First byte of payload is an ICMP Message Type
- ICMP packets typically report errors in the processing of IP packets
  - To avoid recursion of messages about messages, no ICMP messages are sent about ICMP messages
- Now three example ICMP messages ...

ICMP “Echo” and “Echo Reply”

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 0 0 0 1 0 0 0|0 0 0 0 0 0 0 0|          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Identifier                 |        Sequence Number        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    Data (anything) ...
+-+-+-+-+-+-+-+-+-+-+-+-+-
```

Type
- 8 = Echo, 0 = Echo Reply

Identifier
- A random value used to match echo requests and replies

Sequence Number
- Counts up, to match requests and replies in series

Data
- Should be sent back without change

Note: This is what *ping* uses.

ICMP “Destination Unreachable”

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 0 0 0 0 0 1 1|     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             unused                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    IP Header + first 64 payload bits of failed packet         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Code

- 0 = net unreachable
- 1 = host unreachable
- 2 = protocol unreachable
- 3 = port unreachable
- 4 = fragmentation needed but DF set
- 5 = source route failed

Checksum

- 16 bit 1's complement checksum of ICMP message

ICMP “Parameter Problem”

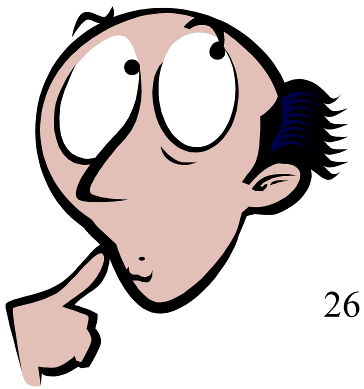
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 0 0 0 1 1 0 0|     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Pointer       |             unused                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    IP Header + first 64 payload bits of failed packet         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Code
- 0 = pointer points to error
- No other values defined

Pointer
- Byte number in failed packet where problem was found

Dynamic Host Configuration Protocol

- For many years, addresses had to be assigned by hand and configured by hand
  - Obviously impractical once PCs appeared by the million
  - DHCP appeared by 1993
- DHCP allows a machine to ask a central server for an address (and other info) when it reboots
  - May be a different address each time, which is OK for clients but inconvenient for servers
- First step is to send a request to the DHCP server
  - But after a reboot, you don't know the address of the DHCP server and you don't have an IP source address to send from. A bit of a puzzle



Oops! DHCP is important, but not detailed in Shay.

Bootstrapping DHCP

- Client starts by *broadcasting* a DHCP DISCOVER message on its LAN
  - Source IP address is 0.0.0.0
  - Destination IP address is 255.255.255.255
  - Destination hardware address is LAN broadcast
  - DISCOVER message includes client's LAN hardware address
- DHCP server will catch the broadcast and reply with a DHCP OFFER message
  - An OFFER message includes a fresh IP address for the client
  - Source address is the DHCP server's own IP address
  - Destination IP address is the offered IP address
  - Destination hardware address is the one supplied by the client

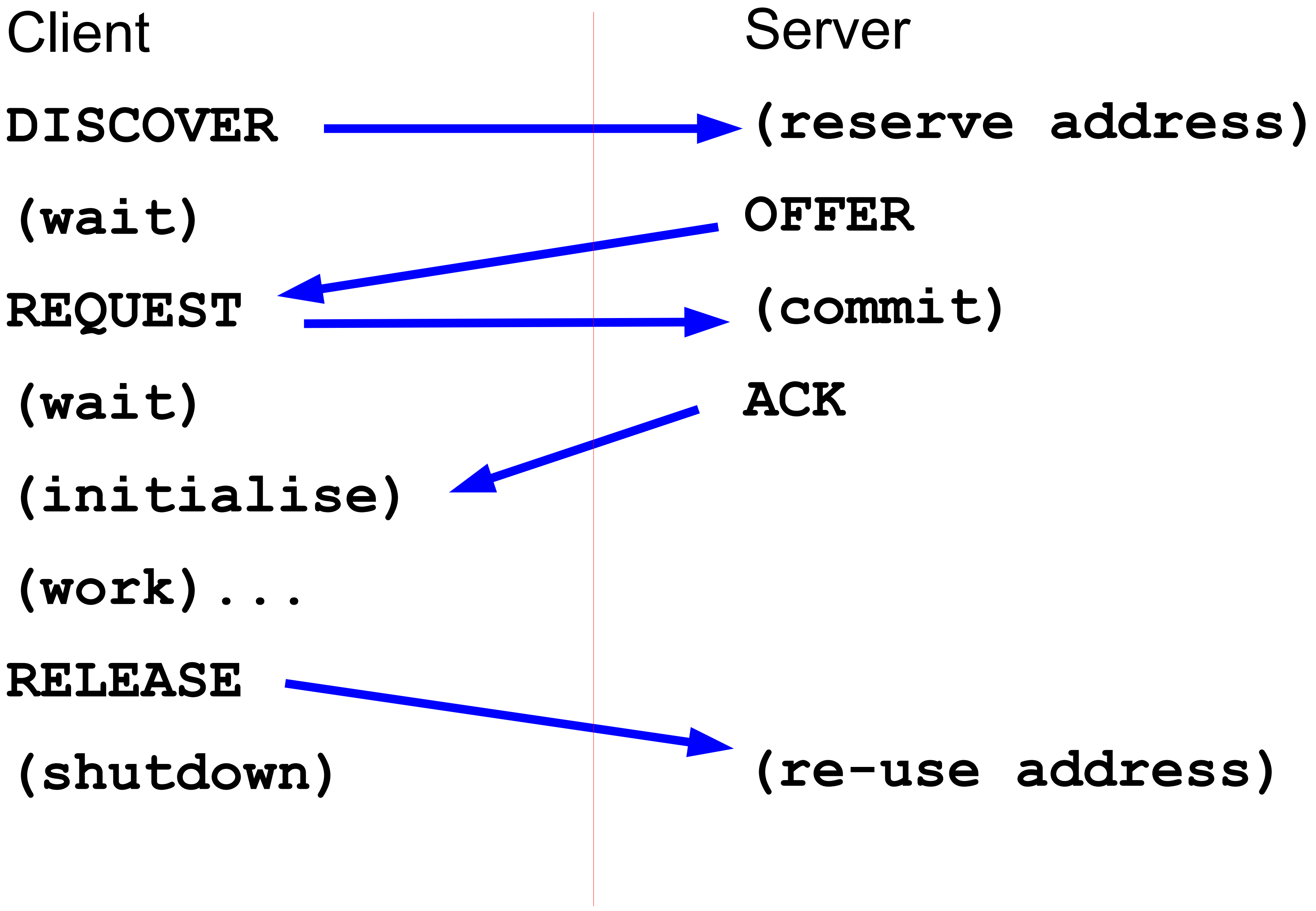
Some DHCP details

- DHCP is built up from an older bootstrap protocol called BOOTP
  - BOOTP and DHCP messages are sent over UDP (to be discussed later), not raw IP
- Either the DHCP server is on the LAN, or a 'DHCP relay' (built into a router) will catch the DHCP DISCOVER and send it on
- There can be several DHCP servers and several DHCP OFFER messages
  - The client must choose one of them
- DHCP addresses have a lifetime (known as a *lease*)
  - The client must renew after that lifetime expires

DHCP message types

- DISCOVER, OFFER - as above
- REQUEST - client requests to accept OFFER or extend lease
- ACK - server accepts REQUEST
- NAK - server denies REQUEST or expires lease
- DECLINE - client rejects OFFER
- RELEASE - client has finished with address
- INFORM - client has address, but requests other parameters

Normal DHCP sequence



Other information (optionally) supplied by DHCP

- DHCP now has >100 optional parameters
  - Default router address(es) ('default gateway')
  - Static routes
  - Local net mask
  - DNS server address
  - Parameters for MTU discovery
  - Parameters for router discovery
  - Type of Ethernet encapsulation
  - ...
  - Mail server addresses
  - Timezone information
  - Physical location data (street address etc.)

Finding Neighbours: Address Resolution Protocol

- Suppose you have an IP address from DHCP as well as the IP address of the default router
  - You: 130.216.1.17
  - Router: 130.216.1.1
- By definition, the default router is on your LAN, but how do you know its Ethernet address?
  - That is the problem ARP solves
- Concept
  - Broadcast an ARP Request asking for 130.216.1.1
  - That host unicasts an ARP Reply
  - Cache the Ethernet address found in the Reply

Oops! ARP is important, but not detailed in Shay

ARP message format (on Ethernet)

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Hardware type = 1             |  Protocol type = 0x0806       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| HwAddrLength  | ProtoAddLgth  | ARP opcode (Request/Reply)    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Sender Hardware Address (48 bits)               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Sender Protocol Address (32 bits)               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Target Hardware Address (48 bits)               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|               Target Protocol Address (32 bits)               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

ARP message format notes

- ARP is carried directly over Layer 2, not over IP, using Ethertype 0x0806
- Hardware type, etc., allow for use over other LAN types than Ethernet and other protocols than IPv4
- Opcodes: Request = 1, Reply =2
- Target Hardware Address is blank in Request and filled in in the Reply
  - Target and Sender are swapped between Request and Reply

ARP in practice

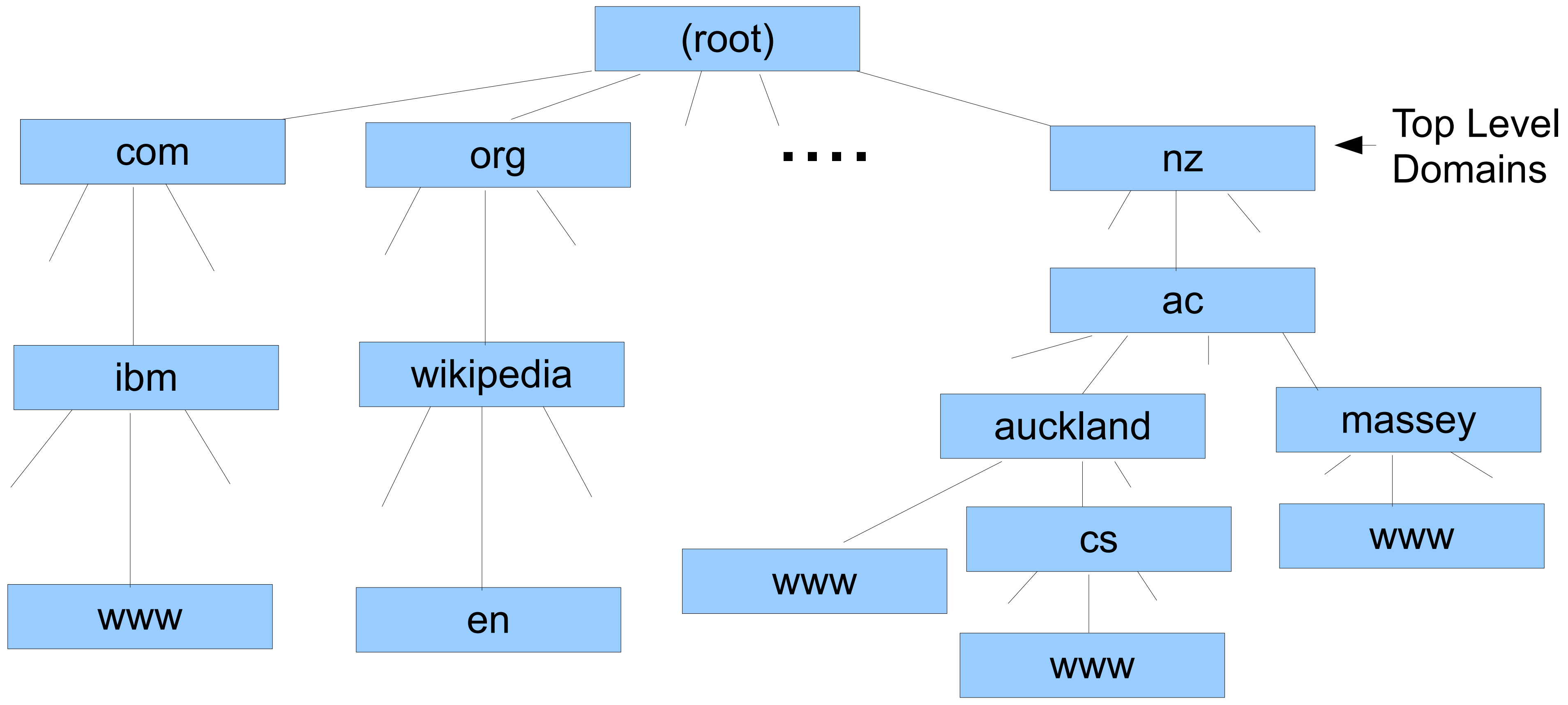
- Clear ARP cache on restart to avoid stale data
- Two Replies to one Request - disaster!
  - Somehow, two hosts believe they have the same address
  - Should not trust either of the replies
- When a host disconnects, DHCP might give its address to someone else - but it's still in your ARP cache - disaster!
  - ARP cache timeout must be short compared to DHCP hold time
  - Unsolicited ARP with **Sender=Target** refreshes the cache
- ARP Reply may come from a proxy (e.g. a bridge)

Let's see where we are ...

- We know what an IPv4 packet looks like
- We know how to get an IPv4 address, default router address, etc. (DHCP)
- We know how to find a neighbour's LAN hardware address, given its IPv4 address (ARP)
- We know how to send a packet, fragment and reassemble packets, and handle packet level errors (ICMP)
- We know how to route off the LAN (RIP, OSPF, BGP4)
- *Missing:* how do we find the IPv4 address of another system from its name?

Naming Things: DNS (Domain Name System)

- Basic concept: unique names in a structured tree
  - Tree is string-based, n-ary (not binary)



DNS names

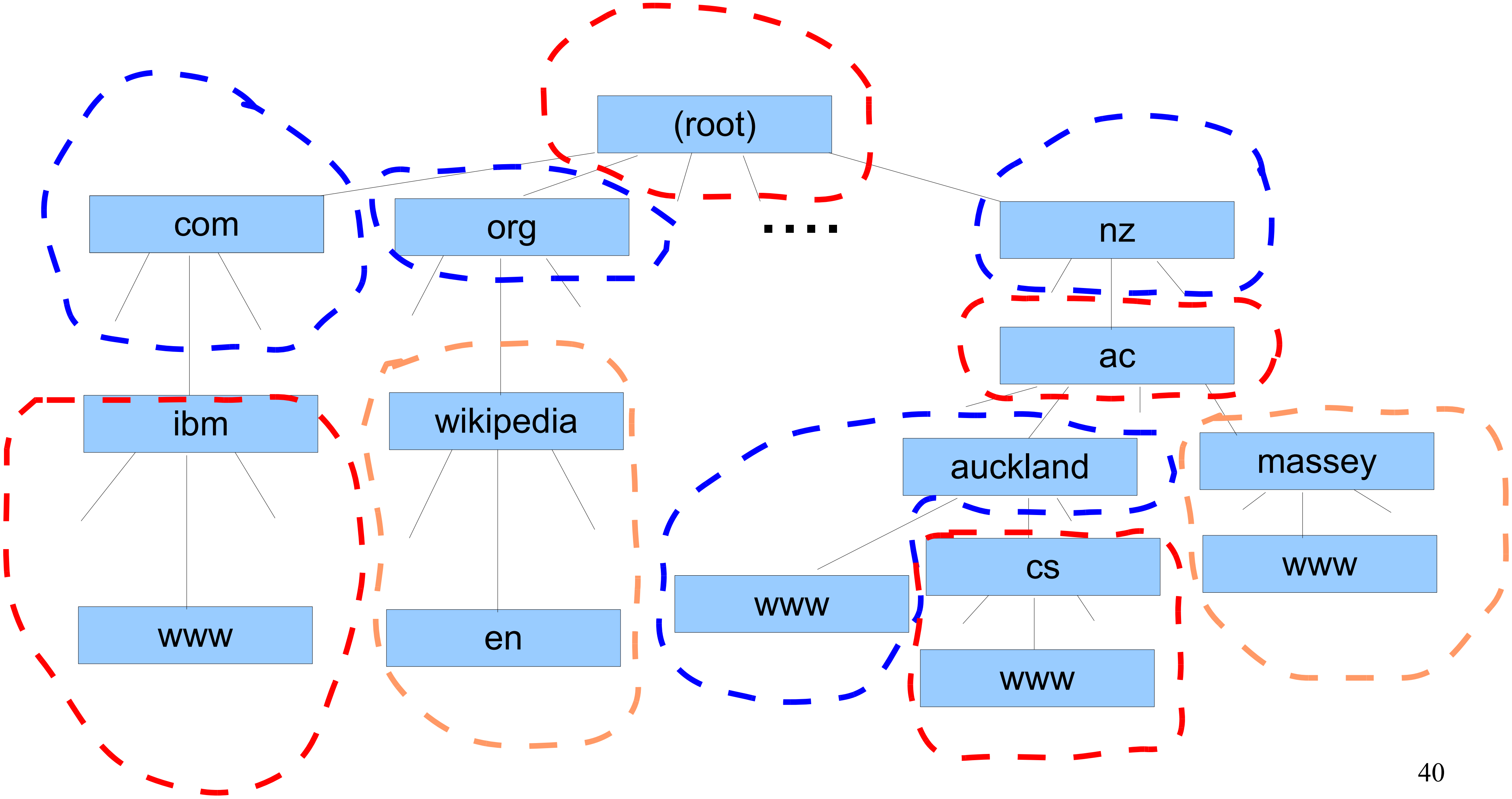
- *www.auckland.ac.nz* and *www.cs.auckland.ac.nz* are FQDNs - Fully Qualified Domain Names
- They are unique (i.e. represent different leaves on the DNS tree)
  - The DNS must have a unique root
  - Names must be registered to guarantee uniqueness
- TLD (Top Level Domain) names are registered world-wide by IANA (Internet Assigned Numbers Authority)
- Each TLD such as *com* or *nz* has its own registry
- Subdomains such as *ac.nz* and *ibm.com* manage their own registries

DNS is a massive Distributed Database

- The database contains hundreds of millions of entries of several types, called RRs (resource records)
- The most important RR type today is an A record
  - The A record for *www.cs.auckland.ac.nz* contains 130.216.33.106
- When a client machine in Switzerland asks its local DNS server for that A record, how does it get there from Auckland?
  - Obviously, it is impractical for every one of the millions of DNS servers in the world to be pre-loaded with hundreds of millions of RRs
  - Obviously, it would be horribly slow if every lookup of every FQDN had to be sent back to the original registry that registered it

Divide and Conquer: DNS Zones

- The namespace is divided into hierarchical zones



Authoritative name servers

- Each zone contains NS records for the authoritative name servers for its child zones
  - The root has an NS record for *nz*
  - *nz* has an NS record for *ac.nz*
  - *ac.nz* has an NS record for *auckland.ac.nz*
  - *auckland.ac.nz* has an NS record for *cs.auckland.ac.nz*
  - *cs.auckland.ac.nz* has no NS records - it is a leaf zone
- The authoritative name servers are configured with all RRs for all FQDNs in their zone
  - But not for FQDNs in child zones; those are delegated
  - Configuration is often done from an equipment database, and requires careful clerical work

Finding the RRs for a given FQDN

- Our problem is reduced to finding the address of the authoritative server of the domain containing those RRs
- Every host includes code called a *resolver* which takes an FQDN and returns an RR
  - A full resolver interacts with mutiple DNS servers in sequence
  - A simple resolver interacts with one “recursive” DNS server
  - In both cases, the lookup process is the same
  - Resolver, or recursive server, sends DNS Request messages
  - Servers send DNS Response messages

Illustrative full DNS lookup

- Resolver is pre-configured with well-known IP addresses of the *root servers* and knows nothing else
- DNS Request to a root server for NS record of *nz*
  - DNS Response with *nz* servers including ns4.dns.net.nz = 203.97.40.200
- DNS Request to ns4.dns.net.nz for NS record of *ac.nz*
  - DNS Response with *ac.nz* servers including ns6.dns.net.nz = 204.74.113.253
- DNS Request to ns6.dns.net.nz for NS record of *auckland.ac.nz*
  - DNS Response with *auckland.ac.nz* servers including dns1.auckland.ac.nz = 130.216.1.2
- DNS Request to dns1.auckland.ac.nz for A record of *www.auckland.ac.nz*
  - DNS Response 130.216.11.202

Making DNS scale to trillions of requests per day

- That means avoiding full lookup in most cases
- Principle: all zones have a defined TTL (time to live). All DNS servers and resolvers may cache any RR found in a DNS Response until its zone TTL expires
  - You really shouldn't be looking up *.com* or *.nz* all the time!
  - Since TTL may be long (days), DNS updates sometimes lag unless somebody flushes the resolver cache
  - For example, *cs.auckland.ac.nz* has TTL=1 day. A resolver that has cached it will not see any change until tomorrow
- Practice: load sharing within a zone
  - Most zones of any size operate multiple parallel DNS servers to provide load sharing and backup
  - Zone files must be kept identical between them

Many other aspects of DNS

- This was an overview. We don't have time for:
  - DNS message formats (sent over UDP)
  - Reverse lookup (getting from an IP address to an FQDN)
  - Dynamic DNS updates (to avoid clerical work)
  - DNS Security (to prevent DNS spoofing)
  - Creative uses of DNS
  - DNS operational pitfalls
- DNS is the only example of a successful distributed database that is deployed worldwide on hundreds of millions of systems. Its designer (Paul Mockapetris) deserves great credit

Summing up on IPv4 ...

- We know what an IPv4 packet looks like
- We know how to get an IPv4 address, default router address, etc. (DHCP)
- We know how to find a neighbour's LAN hardware address, given its IPv4 address (ARP)
- We know how to send a packet, fragment and reassemble packets, and handle packet level errors (ICMP)
- We know how to route off the LAN (RIP, OSPF, BGP4)
- We know how to find the IPv4 address of another system from its FQDN (DNS)

References

- Shay 11.1, 11.2
  - Bug:
    - Talks about Class A, B, C addresses in present tense
- Amazon will find you good books on TCP/IP by
  - Douglas E. Comer and David L. Stevens
  - W. Richard Stevens
  - Pete Loshin
- Many RFCs, but the older ones are hard to understand. Try RFC 1122, but today the only true definition is the running code in Linux, Windows, etc.