Introduction to Computer Networks and the Internet
COSC 264
IP and Related Protocols

Dr. Andreas Willig

Dept. of Computer Science and Software Engineering
University of Canterbury, Christchurch

UoC, 2020

Outline

1. IPv4
   - Packet Format
   - IP Addressing
   - IP Forwarding and Routing
   - Fragmentation and Reassembly
2. IP Helper Protocols
   - ARP
   - ICMP

About This Module

- Goals of this Module:
  - Get a first idea of the Internet
  - Get to know the IP protocol and important support protocols
- Useful references:
  - The “bible” on TCP/IP: [9] (old, but still great!)
  - Other references: [4], [8, Part V]
  - Internet protocols are published as **requests-for-comment** (RFC) by the Internet Engineering Task Force (IETF), you can access them via: `http://www.ietf.org/rfc.html`
- Most of these slides are based on [9]

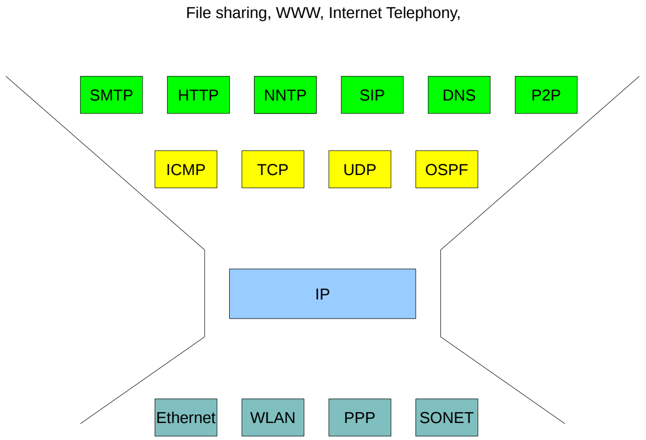
The Internet

- The Internet is a packet-switched network
- It is a **network of networks**:
  - It consists of many different networks, connected by routers
  - The networks or links can be of any technology:
    - Ethernet
    - Optical point-to-point links
    - Wireless LAN
    - …
    - Carrier pigeons (RFC 1149)
- It is really large:
  - The Internet Systems Consortium estimates $\approx$ 1.033 billion stations (called hosts) as of July 2015
  - See `https://www.isc.org/network/survey`
- It has a fairly complex topology [1]

The Internet (2)

- The end-to-end principle [7]:
  - Perform intelligent functions in hosts, not in routers
  - For example:
    - Routers know how to deliver packets
    - All functions making this delivery **reliable** are performed in the end host, e.g. by the TCP protocol
    - There is no network-layer mechanism for reliable delivery
    - **Keep the routers simple!**
- Internet is standardized by the IETF, standards are called RFCs
  - IETF = Internet Engineering Task Force (`www.ietf.org`)
  - RFC = Request For Comment
- For the design philosophy see [3]

The Hourglass Model for the Internet Protocol Stack



- “Everything over IP, IP over everything”

Outline

Introduction

- IP is specified in RFC 791 and many followup RFCs
- It is the network layer protocol of the Internet
- Some terminology:
  - IP packets are called **datagrams**, except if they result from fragmentation and reassembly, then they are called **fragments**
  - End stations are called **hosts**
  - IP routers are called **routers**
- IP addresses are assigned to **network interfaces**:
  - When a host has three Ethernet adapters, it has three IP addresses, one for each adapter
  - Since most hosts have only one adapter, we may speak of the IP address of that host

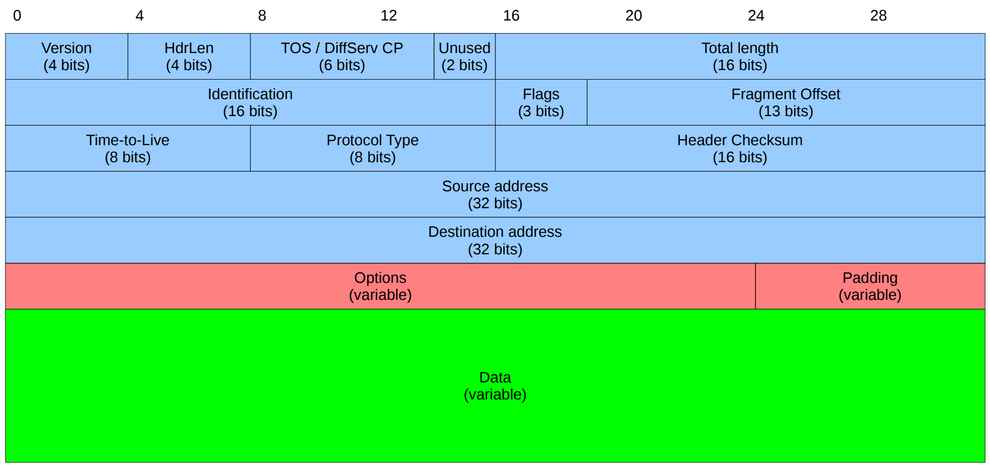
IP Service – Best Effort

- Basic IP service is **datagram delivery**
- This service is:
    - Connectionless: no connection or shared state is set up before datagram delivery starts
    - Unacknowledged: IP does not use acknowledgements
    - Unreliable: on IP level no retransmissions are carried out
    - Unordered: IP does not guarantee in-sequence delivery [2]
- This kind of guarantee-nothing service is called **best effort**

Outline

1. IPv4
    - Packet Format
    - IP Addressing
    - IP Forwarding and Routing
    - Fragmentation and Reassembly
2. IP Helper Protocols

Packet Format



<table>
<tr><td colspan="4">0</td><td colspan="4">4</td><td colspan="4">8</td><td colspan="4">12</td><td colspan="4">16</td><td colspan="4">20</td><td colspan="4">24</td><td colspan="4">28</td></tr>
<tr><td colspan="4">Version
(4 bits)</td><td colspan="4">HdrLen
(4 bits)</td><td colspan="6">TOS / DiffServ CP
(6 bits)</td><td colspan="2">Unused
(2 bits)</td><td colspan="16">Total length
(16 bits)</td></tr>
<tr><td colspan="16">Identification
(16 bits)</td><td colspan="3">Flags
(3 bits)</td><td colspan="13">Fragment Offset
(13 bits)</td></tr>
<tr><td colspan="8">Time-to-Live
(8 bits)</td><td colspan="8">Protocol Type
(8 bits)</td><td colspan="16">Header Checksum
(16 bits)</td></tr>
<tr><td colspan="32">Source address
(32 bits)</td></tr>
<tr><td colspan="32">Destination address
(32 bits)</td></tr>
<tr><td colspan="24">Options
(variable)</td><td colspan="8">Padding
(variable)</td></tr>
<tr><td colspan="32">Data
(variable)</td></tr>
</table>

Packet Format (2)

- Where applicable (e.g. addresses), header is using **big endian** byte ordering (also called **network byte order**)
- The `Version` field specifies the version of the IP protocol running, always 4 for IPv4
- The `HdrLen` field:
    - specifies the length of IP header as number of 32-bit words
    - If the `Options` field does not use a multiple of 32 bits, a `Padding` field is used to fill up to 32 bits
    - When `HdrLen` > 5, then an `Options` field is present
- The `TOS/DSCP` field:
    - TOS = Type Of Service, DSCP = DiffServ Code Point
    - Allows to mark packets for differentiated treatment to achieve Quality-Of-Service (QoS), e.g. express priorities
    - DiffServ [5] is framework for Internet QoS, another is IntServ [10]
    - Many routers ignore the `TOS/DSCP` field

Packet Format (3)

- The `TotalLength` field:
  - Gives the total length of datagram in bytes (i.e. up to 65,535)
  - Can be modified during **fragmentation and reassembly**
  - The `TotalLength` field is part of IP header, since some technologies (Ethernet!) pad up frames to achieve minimum frame size and do not reverse or mark this
- The `Identification` field:
  - Uniquely identifies each IP payload unit accepted from higher layers for a given interface
  - Incremented by source host for each new IP payload
  - In other words: it is a sequence number
  - Routers do not touch this field
- The `Flags` field:
  - Contains two flags relevant for fragmentation and reassembly (`DF`, Don't Fragment, and `MF`, More Fragments)

Packet Format (4)

- The `FragmentOffset` field:
  - Is used for fragmentation and reassembly
  - Gives the offset of the current fragment within entire datagram, in multiples of eight bytes
- The `HeaderChecksum` field:
  - Is calculated over IP header only, not the data (TCP, UDP etc. have their own checksums to cover their data)
- The `Time-To-Live` field:
  - Gives upper limit to number of routers a packet can traverse
  - Decremented by each router, forces re-computation of checksum
  - When `TTL=0` and packet cannot be directly delivered to destination, datagram is discarded, sender is notified (ICMP message)
  - Typical initial values: 32 or 64
  - Intended usage: eliminate packets caught in a routing loop

---

Packet Format (5)

`Protocol` value	Encapsulated Protocol
`0x01`	ICMP
`0x02`	IGMP
`0x04`	IP-in-IP Encapsulation
`0x06`	TCP
`0x11`	UDP

- `Protocol` field indicates the higher-layer protocol that generated the payload
- This field provides **protocol multiplexing**
- In other words: it provides different SAPs
- Some values shown in table

Packet Format (6)

- The `SourceAddress/DestinationAddress` fields:
  - `SrcAddr` indicates the initial sender of datagram
  - `DstAddr` indicates intended final receiver of datagram
  - Are of 32 bits width
- The `Options` field:
  - Contains header field for optional IP features
  - One example option: source routing
  - Options are rarely used, we will not consider this anymore

Outline

1. IPv4
   - Packet Format
   - IP Addressing
   - IP Forwarding and Routing
   - Fragmentation and Reassembly
2. IP Helper Protocols

IP Address Representation

- IP addresses have a width of 32 bits
- They are supposed to be worldwide unique
  - This is not really true anymore with NAT ...
- IP addresses are written in **dotted-decimal notation**, e.g.:

  `130.149.49.77`

  where decimal (!) numbers are separated by dots
- They have an internal structure:

  `<network-id> <host-id>`

  where:
  - `<network-id>` denotes a network (e.g. an Ethernet)
  - `<host-id>` refers to a host **within** this network
- The `<host-id>` must only be unique w.r.t. its network

Interlude: Routing / Forwarding Tables

- IP routers have several network interfaces or ports (different from TCP/UDP port numbers) where they receive/transmit datagrams
- In IP networks a router getting a packet on some input port looks at the `DestinationAddress` field to determine the output port
- The router consults a **forwarding table**:
  - The forwarding table lists all networks the router knows with their `<network-id>` and the output port to send the packet to in order to reach that network
  - The router performs a **table lookup** for an incoming packet, it searches the forwarding table for a matching network entry
  - Time required for table lookup depends on number of table entries
  - How this table is filled is determined by a separate routing protocol
- This is simplified, more details later!

Important Points

Important Point

A host address is tied to its location in the network, i.e. it is coupled to network topology. When a host switches to another network, it obtains another address and ongoing connections (TCP!) break – IP therefore has no direct support for mobility!!

Important Point

IP Routing is mostly concerned with networks, i.e. forwarding tables in routers mostly store `<network-id>`'s – it is the responsibility of last router on a path to deliver an IP datagram to directly connected host.

Classless Inter-Domain Routing

- Question: how many bits to allocate to `<network-id>`?
- In the early days, this number was fixed to three different values (classful addressing)
- This proved inflexible, something better was needed
- CIDR = Classless Inter-Domain Routing
- Introduced 1993, specified in RFCs 1518, 1519, mandatory
- Modern routing protocols (OSPF, RIPv2, BGP) use CIDR
- In CIDR a network is specified by two values:
  - A 32 bit network address
  - A 32 bit network mask (**netmask**)

CIDR – Netmask

- For a given 32-bit IP address the netmask specifies which bits belong to network-id and which bits belong to host-id
- The netmask consists of 32 bits, the leftmost *k* bits are ones, the remaining $32 - k$ bits are zeros
- Examples:

Netmask	**Shorthand**
`11111111.11110000.00000000.00000000`	/12
`11111111.11111111.00000000.00000000`	/16
`11111111.11111111.11100000.00000000`	/19
`11111111.11111111.11111110.00000000`	/23

- To fully specify network, give network address and netmask, e.g.:

`192.168.40.0/21`

- The rightmost $32 - k$ bits of network address `a.b.c.d/k` are zero

---

CIDR – Netmask (2)

- Example: given host address `192.168.40.3` and netmask /24, the hosts network address is computed as:

	`11000000.10101000.00101000.00000011`	`192.168.40.3`
AND	`11111111.11111111.11111111.00000000`	/24
	`11000000.10101000.00101000.00000000`	`192.168.40.0`

- The same example, now with netmask /21:

	`11000000.10101000.00101000.00000011`	`192.168.40.3`
AND	`11111111.11111111.11111000.00000000`	/21
	`11000000.10101000.00101000.00000000`	`192.168.40.0`

- In both examples the network addresses are the same, but the networks are of different size
- To distinguish both networks you need to specify both network address and bitmask, network address alone is insufficient

---

CIDR – Netmask (3)

- In a network `a.b.c.d/k` there are two “special host addresses”:
  - The host address `000..00` (with $32 - k$ zeros in total) is part of the network id, signifying that we refer to the network as a whole
  - The host address `111..11` (with $32 - k$ ones in total) is the broadcast address of this network

  All the other host addresses can be assigned to individual hosts
- Example: In the network `192.168.40.64/28` there are 14 addresses available:
  - The netmask leaves four bits for the host-id, i.e. 16 values
  - The value `0000` is part of the network-id
  - The value `1111` is the broadcast address for this network

Reserved IP address blocks

Address Block	Current Usage
`10.0.0.0/8`	Private-use IP networks
`127.0.0.0/8`	Host loopback network
`169.254.0.0/16`	Link-local for point-to-point links (e.g. dialup)
`172.16.0.0/12`	Private-use IP networks
`192.168.0.0/16`	Private-use IP networks

(from: [6], there are more than shown here)

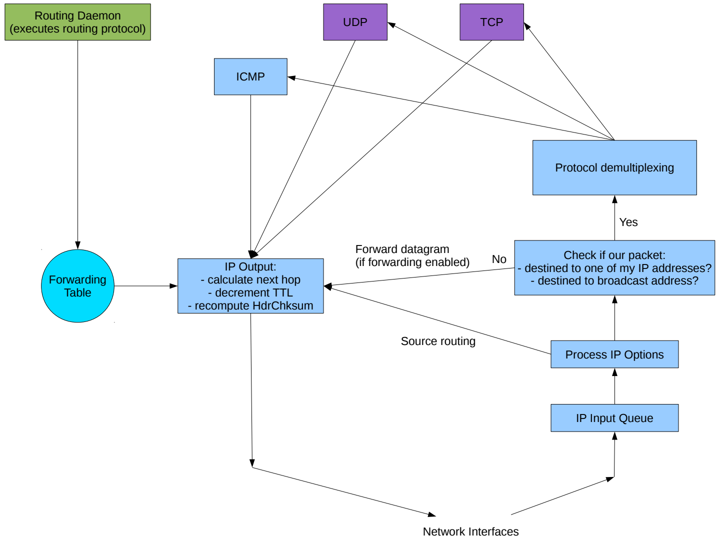
- Private-use IP addresses are often used for broadband clients or by NAT boxes
- The “traditional” loopback address of a host is `127.0.0.1`, but any address from `127.0.0.0/8` network serves same purpose
- Packets with private addresses are not routed in the public internet, only within the provider network

---

Outline

1. IPv4
   - Packet Format
   - IP Addressing
   - IP Forwarding and Routing
   - Fragmentation and Reassembly
2. IP Helper Protocols

Simplified Packet Processing



Simplified Packet Processing (2)

- Packet processing chain is followed in routers and hosts
- Incoming packets are checked for correctness and stored in IP input queue – correctness includes:
  - right value in IP version field
  - correct IP header checksum
- Next, packet options are processed (rarely used)
- Next, it is checked if packet is destined to **this** host / router or to the broadcast address of any network this host / router is directly attached to
- If so, protocol demultiplexing is carried out
  - The `Protocol` field in IP header is checked for its value
  - Packet payload is delivered to the software entity implementing the indicated higher-layer protocol
  - Packet is not processed any further!

Simplified Packet Processing (3)

- If packet is not destined to this host/router or broadcast address:
  - If packet forwarding is not enabled, the packet is dropped
  - Otherwise:
    - Check if packet is destined to a directly reachable station (e.g. on a directly attached Ethernet) – if so, deliver packet directly
    - If packet is not destined to directly reachable station, consult forwarding table to determine next hop / outgoing interface
    - Decrement TTL value, drop packet when it reaches zero
    - Recompute packet header checksum (why?)
    - Hand packet over to outgoing interface
- Forwarding table is maintained by a **routing daemon**, i.e. a process executing a routing protocol
- Note that datagrams to be routed can come from local applications or from other hosts via IP input queue
- Linux commands to inspect / modify forwarding table:
  - `netstat`
  - `route`

Forwarding Table Contents (First Approximation)

- Each entry in the forwarding table contains:
  - Destination IP address, which can be either:
    - a full host address (i.e. non-zero host-id)
    - a network address, with netmask

    depending on the value of a flag
  - Information about next hop, either:
    - IP address of next-hop router (must be directly reachable)
    - IP address of directly-connected network (network address)
  - Flags:
    - A flag telling whether destination IP is host or network
    - A flag telling whether next hop is a router or directly attached network
  - Specification of outgoing interface

Forwarding (First Approximation)

- From forwarding table structure it is clear that a host / router does not know the full path, but only next hop
- Forwarding table lookup for a packet with destination IP address `dst` proceeds in three stages (Caveat: reality is different):
  - First look for an entry that is a full-host address matching `dst` – if found, send packet to indicated next hop / outgoing interface and stop processing
    - This is not used very often
  - Next look for an entry that is a network address matching `dst` – if found, send packet to indicated next hop / outgoing interface and stop processing
  - Finally look for special **default** entry – if found, send packet to indicated next hop (the **default router**) and stop processing
  - Otherwise drop packet, send ICMP message back to original sender of datagram

---

Forwarding – Address Matching

- **Question**: how to check whether a destination address `dst` matches a forwarding table entry for network `a.b.c.d/k`?

Forwarding – Address Matching (2)

- **Answer**: They match when

$$(\mathrm{dst}\ \text{AND} < /\mathrm{k}-\mathrm{netmask} >) \quad == \quad (\mathrm{a.b.c.d}\ \text{AND} < /\mathrm{k}-\mathrm{netmask} >)$$

- **Example**: We are given the following forwarding table:

Destination Network/Netmask	Outgoing interface
`130.1.0.0 / 16`	`eth0`
`141.5.6.0 / 24`	`eth1`

- **Question**: We are given two packets with destination addresses `130.1.9.5`, and `166.42.17.12`, respectively. Which decisions does the router make?
- **Question**: And what happens if a default route is added to the forwarding table?

Forwarding Tables in Hosts

- Most end hosts leverage the **default route** mechanism:
  - An end host can differentiate between packets to local destinations and to all other destinations
    - **Question**: suppose an end host has address `130.149.49.77` and is part of a `/24` network – how does it check whether a destination address `a.b.c.d` belongs to another host in the same network?
  - Packets to local destinations are delivered directly (see discussion of ARP for how to do this in an Ethernet)
  - Packets to all other destinations are sent to default router
- Therefore, forwarding tables in end hosts can be made out of just two (or more generally: a few) entries:
  - One entry for each network it is directly attached to
  - The default route
- The default route must be configured (typically done by DHCP)

Forwarding Tables in Routers

- Most routers at the “border” of the Internet only have forwarding table entries for a subset of all networks attached to the Internet (likely other networks belonging to the same owner), for all other networks they rely on default routers
- Some routers in the core:
  - do not have a default router
  - are the default routers of other routers
  - must know (almost) all the Internet networks

Outline

On the Choice of Packet Size

- The link-layer technologies underlying IP offer many different maximally allowed packet sizes, e.g.:
  - Ethernet: 1500 bytes
  - Gigabit Ethernet: 9000 bytes
  - IEEE 802.11 WLAN: 2312 bytes
  - ISDN: 576 bytes
- This max size also known as **maximum transmission unit** (MTU)
- Higher-layer protocols (TCP, UDP) and applications should not be required to know these maximal sizes:
  - One reason: "software hygiene", separation of concerns
  - Another reason: it is not well defined:
    - Different packets of the same flow can take different routes
    - A packet can use different technologies while in transit
    - Even if all packets use the same route, this route can change due to link failures / restores

---

Fragmentation and Reassembly

- IP **hides** this from upper layers, offers own maximum message length of 65,515 bytes to higher layers
  - 65,515 = 65,535 - 20, 20 bytes is minimum size of IP header
- To cope with smaller MTUs:
  - Sender IP instance partitions message into **fragments**
  - Each fragment is transmitted individually as a full IP packet, with header information specifying that this is a fragment and giving the position of fragment in whole message
  - Each fragment has a size no larger than MTU of outgoing link
  - IP instance at destination buffers received fragments, re-assembles message and delivers it to higher layers

Question

Would it be useful to have intermediate IP routers perform reassembly?

Fragmentation and Reassembly (2)

- In addition, every intermediate router can:
  - fragment a full message
  - further fragment a fragment

  when necessary for transmission on next hop
- When the destination receives the first fragment, it:
  - Allocates buffer large enough for whole message
  - Starts a timer
- When all fragments arrive before timer expiration:
  - Timer is canceled
  - Re-assembled packet is handed over to higher layers
  - Buffer is de-allocated
- When timer expires before all fragments have arrived:
  - The already received fragments are dropped, buffer is freed
  - ICMP message (type 11, code 1) is sent to source host

Some Details

- Every message handed over from higher layers has own identifier
  - See `Identification` field in IP header
- All fragment datagrams belonging to same message have:
  - A full IP header
  - The same value in the `Identification` field
  - A `TotalLength` field reflecting the fragment size
  - Different values for `FragmentOffset` field (reflecting the start of the present fragment within the whole message):
    - `FragmentOffset` specifies offset in multiples of 8 bytes
  - The `MF` (more-fragments) bit set, except for the last fragment, which has non-zero `FragmentOffset`

Question

With this setup: how much buffer space shall the receiver allocate when collecting fragments?

Some Details: The `DF` bit

- By setting the `DF` (don't fragment) bit in the IP header a source node **forbids** fragmentation by intermediate routers
- When a router receives a datagram with `DF` set, it:
  - Checks whether outgoing link for this packet has an MTU large enough to transmit the packet
  - If so, the packet is transmitted onto next hop
  - If not, the router drops the datagram and returns an ICMP message to original IP source
    - ICMP with type 2 ("destination unreachable") and code 4 ("fragmentation required, but DF set")

Some Details: The `DF` bit (2)

Question

How could you use this for the sender to determine the **path MTU**, defined as the smallest MTU of all links along a path between source and destination?

Fragmentation and Reassembly – Discussion

- Fragmentation/Reassembly creates significant overhead:
  - Several datagrams per message, each having full IP header
  - Reassembly adds significant complexity to receiver
  - Upon loss of single fragment the whole message is possibly re-transmitted by higher layers (TCP!)

Outline

1. IPv4
2. IP Helper Protocols

Outline

1. IPv4
2. IP Helper Protocols
    - ARP
    - ICMP

Address Resolution Protocol – ARP

- IP addresses only have a meaning to IP and higher layers
- In an Ethernet, stations have own 48-bit MAC addresses
- Recall that IP datagrams are encapsulated into Ethernet frames
- An Ethernet station picks up a packet only if the destination MAC address matches its own MAC address (ignoring broadcast / multicast), IP addresses and other packet contents are ignored
- An IP address is assigned to an Ethernet adapter

Important Question

How do other stations know to which MAC address a given IP address refers?

Address Resolution Protocol – ARP (2)

- ARP determines MAC address for given IP address
- ARP is specified in RFC 826
- ARP is not restricted to Ethernet, but in general is geared towards LANs with broadcast capabilities
- ARP is **dynamic**:
    - The MAC address for a given IP address does not need to be statically configured, ARP allows to determine this on-the-fly
    - Advantage: nodes can be moved or equipped with new MAC adapters without any re-configuration
    - Disadvantage: a separate protocol is needed, bringing additional complexity and requiring a little bandwidth
- There is also a protocol that lets stations find an IP address for a given MAC address, this is called RARP (Reverse ARP)

Basic Operation of ARP

- Suppose that:
    - We have two stations *A* and *B* attached to the same Ethernet, having the following addresses:

	Station *A*	**Station *B***
MAC	`11:11:11:11:11:11`	`22:22:22:22:22:22`
IP	`130.149.49.11`	`130.149.49.22`

    - Both *A* and *B* are in the same IP network `130.149.49.00/24`, which is an Ethernet network
    - Station *A* wishes to send an IP packet to address `130.149.49.22` and does not yet have any information about the corresponding MAC address
- Each station maintains an **ARP Cache**, which stores the mappings from IP to MAC addresses that the station currently knows about

Basic Operation of ARP (2)

- Station *A* **broadcasts** an **ARP-request** message (displayed in `wireshark` as `arp who-has`), indicating:
  - *A*'s own IP and MAC address
  - *B*'s IP address

  Broadcasting means: packet is sent to **Ethernet broadcast address**, Ethernet frame has value `0x0806` in the length/type field
- Any host *C* having an IP address other than `130.149.49.22` simply drops the ARP-request packet
- Upon receiving the ARP request, host *B* (with IP address `130.149.49.22`) performs the following actions:
  - It stores a binding between between *A*'s IP and MAC address in its own ARP cache
  - It responds with an **ARP-reply packet** that includes:
    - *B*'s MAC and IP address
    - *A*'s MAC and IP address

    ARP reply is unicast to *A*'s MAC addr. (Why no broadcast?)

Basic Operation of ARP (3)

- Upon receiving ARP response from *B*, station *A* stores a binding between *B*'s IP and MAC address in its ARP cache
- This procedure is called **address resolution**
- ARP makes no retransmissions when ARP request not answered
- If a station wants to send an IP packet to a local destination with address `a.b.c.d`, it:
  - first checks the ARP cache whether a binding for `a.b.c.d` can be found
  - If so, the packet is encapsulated in an Ethernet frame and directed to the MAC address found in the ARP cache
  - Otherwise, the address resolution procedure is started and the packet is sent when the result is available

---

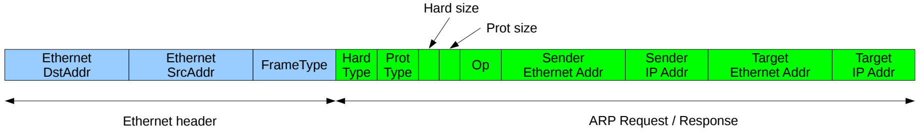
The ARP Cache

- The entries in an ARP cache are soft-state, entries are typically removed 20 minutes after their creation
  - Why?
  - Some implementations restart the timer after each reference to an ARP cache entry
- Under Linux you can inspect your ARP cache with the command:

```
/usr/sbin/arp -a
```

  The path to the `arp` command can vary between systems

The ARP Frame Format



(See [9, Sect. 4])

- `HardType` determines the type of MAC addresses used, `0x0001` for Ethernet 48-bit addresses
- `ProtType` determines the higher-layer protocol for which address resolution needs to be done, value `0x0800` for IP
- `HardSize` and `ProtSize` specify the size (in bytes) of the hardware and and protocol addresses – they are 6 and 4 for Ethernet and IP
- `Op` distinguishes between ARP-request and ARP-reply, and some other types (RARP is covered as well)
- The remaining four fields are the mentioned address fields

Outline

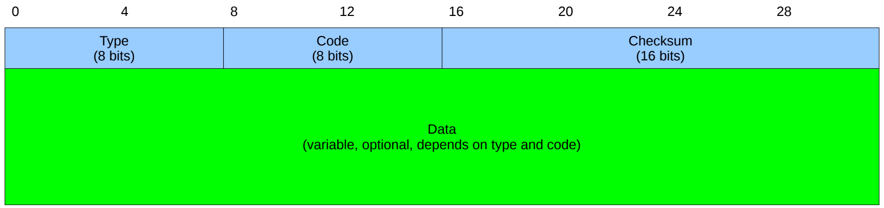
1. IPv4
2. IP Helper Protocols
   - ARP
   - ICMP

Introduction

- ICMP = Internet Control Message Protocol
- Specified in RFC 792
- This protocol:
  - Accompanies the IP protocol by allowing routers or destination hosts to inform sender about “unusual” situations, including:
    - There is no route to the destination
    - Destination host is not reachable
    - Fragmentation required but `DF` set
  - Operates “on top” of IP, i.e. ICMP messages are encapsulated into regular IP datagrams
  - Does not add additional mechanisms (like error control) to IP
  - Does not force any host/router to generate ICMP messages
  - IP sending host **must not rely** on ICMP messages
- These days ICMP messages are often filtered out by firewalls

---

Message Format



- `type` and `code` specify actual ICMP message type and sub-type
- `checksum` covers ICMP header and data, with `checksum` assumed as zero
- `Data` depends on `type`/`code` combination, but often includes the first few bytes of the offending IP datagram (including its header)

Some `type/code` Combinations

`type`	`code`	**Meaning**
0	0	Echo reply
3	0	Destination network unreachable
3	1	Destination host unreachable
3	2	Destination protocol unreachable
3	3	Destination port unreachable
3	4	Fragmentation required, but `DF` bit set
3	6	Destination network unknown
3	7	Destination host unknown
4	0	Source quench (Congestion control)
8	0	Echo request
11	0	TTL expired in transit
11	1	Fragment reassembly time exceeded

- There are many more, e.g. for router advertisements, information about malformed IP packets, etc.
- It is implementation-dependent, which ICMP messages are generated
- ICMP messages are often suppressed by firewalls, otherwise too much information about internal network structures could be revealed

Some `type/code` Combinations (2)

- Source-quench (`type`=4, `code`=0):
  - generated by IP router when it drops a packet due to congestion
  - Intention is to let source host throttle its rate
- TTL expiration (`type`=11, `code`=0):
  - generated by IP router when it drops a packet because its TTL value reached zero
  - **Question**: this is used by `traceroute`. How?
- Fragment reassembly timeout (`type`=11, `code`=1):
  - Generated by destination when not all fragments of a message have been received within timeout
  - Used to invite higher-layer protocol at sending host to re-transmit the message (with all the fragments)
  - IP itself does not perform any retransmission!

Some `type/code` Combinations (3)

- The “destination-unreachable” messages (`type`=3):
  - `code`=0 (destination network unreachable) and `code`=1 (destination host unreachable): generated when:
    - `code`=0: router does not have a matching entry (and no default entry) for non-directly connected destination address in its forwarding table
    - `code`=1: router could not deliver datagram to directly connected host (e.g. no ARP response)
  - `code`=2 (protocol unreachable): IP datagram refers to non-existent higher-layer protocol in destination (cf. IP `protocol-type` field)
  - `code`=3 (port unreachable): used with TCP / UDP
  - In these messages first 32 bits of the variable ICMP message part are 0, following bytes contain IP header and first few bytes of offending IP datagram

[1] David Alderson, Lun Li, Walter Willinger, and John C. Doyle.
Understanding Internet Topology: Principles, Models and Validation.
IEEE/ACM Transactions on Networking, 13(6):1205–1218, December 2005.

[2] Jon C. R. Bennett, Craig Partridge, and Nicholas Shectman.
Packet Reordering is Not Pathological Network Behaviour.
IEEE/ACM Transactions on Networking, 7(6):789–798, December 1999.

[3] David D. Clark.
The design philosophy of the darpa internet protocols.
ACM Computer Communication Review, 18(4):106–114, August 1988.

[4] Douglas E. Comer.
Internetworking with TCP/IP – Principles, Protocols and Architecture, volume 1.
Prentice Hall, Englewood Cliffs, New Jersey, third edition, 1995.

[5] Kalevi Kilkki.
Differentiated Services for the Internet.
Macmillan Technical Publishing, Indianapolis, 1999.

[6] Deepankar Medhi and Karthikeyan Ramasamy.
Network Routing – Algorithms, Protocols, and Architectures.
Morgan Kaufmann, San Francicso, California, 2007.

[7] Jerome H. Saltzer, David P. Reed, and David D. Clark.
End-to-end arguments in system design.
ACM Transactions on Computer Systems, 2(4):277–288, November 1984.

[8] William Stallings.
Data and Computer Communications.
Prentice Hall, Englewood Cliffs, New Jersey, fourth edition, 2006.

[9] W. Richard Stevens.
TCP/IP Illustrated Volume 1 - The Protocols.
Addison-Wesley, Boston, Massachusetts, 1995.

[10] Paul P. White and Jon Crowcroft.
The integrated services in the internet: State of the art.
Proceedings of the IEEE, 85(12):1934–1946, December 1997.