NSWI090: **Computer Networks**

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Lecture 9

Protocols

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2023

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Lecture Outline

IPv4 protocol

- **Datagram structure**
  - Meaning and usage of individual header fields
- **Fragmentation** of datagrams
  - Motivation
  - Strategies
  - Process

Lecture Outline

ICMPv4

- Message structure and basic message types

ARP

- Translation of IP addresses to hardware addresses

RARP

- Translation of hardware addresses to IP addresses

DHCP

- Configuration of nodes including assignment of IP addresses

IPv6

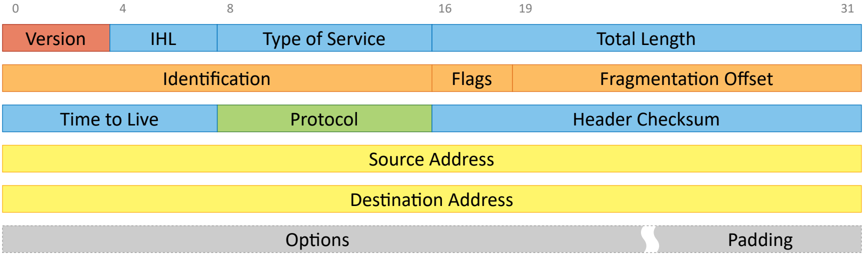
- Packet structure, header fields, and fragmentation

ICMPv6

IPv4 Datagrams

Datagram structure

- **Header**
  - **Required fields** as well as **optional fields** ⇒ **variable length**
    - Must be aligned to integral multiples of 4 bytes
- **Body** (payload)
  - **TCP segment**, **UDP datagram**, …



Header Fields

Version (4 bits)

- Allows to mutually **distinguish** individual L3 **protocols**
  - **Fixed to value 4** (for IPv4)
    - Analogously, IPv6 has value 6 at the same position

Type of Service (**ToS**) (8 bits)

- Kind of a *forgotten byte*
  - Its exact originally intended meaning is no longer known
- **Various purposes over the years**
  - Redefined for several times and never actually used widely
  - Always related to various **Quality of Service** aspects
    - Nowadays ignored
    - Or exploited within **DiffServ** (**Differentiated Services**)

Header Fields

Internet Header Length (IHL) (4 bits)

- Overall **header length**
  - Expressed in integral multiples of 4 bytes
- **Only compulsory header fields are usually present**
  - And so the minimal header length is also the usual one
    - I.e., 20 bytes (IHL = 5)
  - 4 bits are available ⇒ maximal length is 60 bytes (IHL = 15)

Total Length (16 bits)

- Overall **datagram length**
  - I.e., header and body (payload) together
- 16 bits are available ⇒ **maximal IP datagram size is 64 kB**
  - Much smaller datagram sizes occur in practice, though
    - Because of MTUs introduced by real-world L2 technologies

Header Fields: TTL

Time to Live (**TTL**) (8 bits)

- **Limits a time for which a given datagram is supposed to exist**
  - Originally intended as a real-world time in seconds
  - Nowadays used as a **Hop Count**
    - Works as a **decreasing counter**
  - Protects from indefinite dissemination caused by **loops**
- Sender sets TTL to a certain **initial value**
  - Maximal value is 255, recommended initial is 64
- **Each router** on the way…
  - Current TTL value is **decremented by 1**
  - Datagram is / should be **discarded when 0 is reached**
  - In such a case, original sender is notified
    - Via an **ICMP** **Time Exceeded** message

TraceRoute Tool

`traceroute` (`tracert`)

- **Diagnostic tool** allowing for retrieval of **routing paths**
  - I.e., **sequence of routers** on the way to a given target node
    - Including individual measured transit delay times

Basic principle

- **TTLs are intentionally set to very low values**
  - Starting with 1, then gradually increasing, always by 1
- So that **routers on the way are hence pushed to discarding**
  - Causing such routers to reveal their existence
    - As well as providing their IP addresses in particular

TraceRoute Tool

Overall process

- IP datagrams with **ICMP** **Echo Request** payloads are iteratively sent in a loop, step by step
  - Each time a higher TTL value is used
- When **ICMP** **Echo Reply** response is received
  - Whole process ends
    - Since the destination node was already reached
- When **ICMP** **Time Exceeded** response is received
  - Another router on the way was detected
  - And the whole process continues…
- When **no response is received within a given timeout**
  - Another router was also detected
    - But no information is available

Header Fields: Header Checksum

Header Checksum (16 bits)

- Aims at **ensuring header integrity**
  - I.e., allows for detection of potential changes in header fields
- **Does not involve payload content**
  - Its integrity must be treated by L4 if need be

Checksum **calculation**

- Header is interpreted as a **sequence of 16-bit words**
- **Ordinary checksum** (not CRC) is calculated
  - Checksum field as such is skipped
  - Potential overflow area is summed as well
  - **One's complement** is in fact used as the final check value
    - I.e., individual bits are inverted

Header Fields: Header Checksum

Verification

- Checksum is calculated over absolutely all header fields
  - I.e., including the checksum field itself
- **When 0 is obtained**, no damage was detected
- Otherwise whole **datagram** can be / is **discarded**
  - In which case the **sender is not notified**!
  - I.e., **no ICMP message is sent**
    - Since even the source address could have been damaged
    - And so there is no guarantee the real sender would be notified

Observation: **checksum must be recalculated**…

- **Each time TTL is decremented**
  - Which is quite often = whenever passing through any router
- As well as whenever NAT **is applied** / fragmentation **occurs**

Header Fields: Protocol

Protocol (8 bits)

- **Allows to distinguish different types of data in the payload**
  - I.e., individual L4 transport protocols (TCP, UDP, …)
    - Including L4 control protocols (RSVP, …)
  - As well as **internal L3 control protocols** (ICMP, IGMP, …)
    - Since they also encapsulate their messages into IP datagrams
- Maintained by **IANA**
  - https://www.iana.org/assignments/protocol-numbers/
    - Almost 150 values out of 256 are currently assigned
- Examples
  - **UDP** (17), DCCP (33), SCTP (132), **TCP** (6)
  - **ICMP** (1), IGMP (2), RSVP (46)
  - **IPv6** (41) – encapsulation of IPv6 packets in IPv4 datagrams
  - …

Header Fields: Options

Options

- **Allow to specify additional optional information**
  - So that standard handling of IP datagrams could be adjusted
    - Not used frequently nowadays, though
- **Arbitrary number** of options can be specified (0 or more)
  - Each may have a different size (both **fixed** or **variable**)
  - Overall size of all options must aligned to multiples of 4 bytes
    - If not, extra **padding** must be added at the end

Generic **internal structure**

- **Option Type** (1 byte)
- **Option Length** (1 byte) – omitted in fixed-length options
- **Option Data** (0 or more bytes) – omitted in simple options

Header Fields: Options

Option types

- Maintained by **IANA**
  - https://www.iana.org/assignments/ip-parameters/
    - Altogether $\approx$ 25 options are currently defined
- Have their **internal structure**, too
  - **Copied Flag** (1 bit)
    - Related to the process of **fragmentation of IP datagrams**
    - Indicates whether an option should be copied into fragments
  - **Option Class** (2 bits)
    - Describes the intended usage (control, debugging, …)
  - **Option Number** (5 bits)
    - Specifies a particular option type

Header Fields: Options

Option examples

- **End of Option List** (**EOOL**, 0, not copied)
  - Used for **padding** purposes
- **Time Stamp** (**TS**, 68, not copied)
  - Allows to record time delays between individual routers
- **Options used by Source Routing at L3**
  - **Record Route** (**RR**, 7, not copied)
    - Allows to record IP addresses of individual routers on the way
    - Used for probe datagrams during the first phase
  - **Strict Source Route** (**SSR**, 137, copied)
    - Sequence of routers prescribing the intended datagram routing
  - **Loose Source Route** (**LSR**, 131, copied)
    - Analogous idea, only additional previously unspecified routers might be visited between the compulsory specified ones

Header Fields

Source Address and Destination Address (32 bits each)

- Standard IPv4 sender / recipient addresses

Fragmentation

Motivation: **block transmissions**

- There is always a certain **limitation on acceptable block sizes**
  - Regardless of a particular layer or protocol
- Expressed via Maximum Transmission Unit (**MTU**)
  - Defines **maximal payload size** a protocol is willing to accept
    - And so guaranteeing it is capable to transmit
    - Of course, using the services of the lower layer
- ⇒ **it may happen that MTU of the lower layer is insufficient**
  - In terms of the whole prepared PDU we want to transmit
    - I.e., including our header / footer
  - In such a case, **transmission would need to be rejected**
- **Solution**: **oversized block is split into smaller** fragments
  - Each of which has size which already is acceptable

Fragmentation

Ultimate **objective**

- Need for **fragmentation should be avoided** whenever possible

Avoidance strategies

- **Providing illusion of a byte stream**
  - So that the higher layer does not need to be aware of anything
    - But, of course, that only moves the problem elsewhere…
  - Example: **TCP**
- **Announcing non-fragmenting MTUs**
  - I.e., **maximal size ensuring no fragmentation will be needed**
    - This recommendation is provided to the higher layer
    - In the expectation that this layer will simply respect it
    - I.e., that it will only create blocks of suitable sizes
  - Examples: **IP** $\rightarrow$ **TCP** or also **IP** $\rightarrow$ **UDP** $\rightarrow$ L7

IPv4 Fragmentation

Observation

- **Fragmentation avoidance is not always achievable**
  - Because the announced MTUs may not be **respected**
  - Or MTUs as such might not have been correctly **resolved**
- And so fragmentation has to inevitably be somehow supported

Deployment at L3 in IPv4

- Fragmentation of IP datagrams is supported
  - And so must be the subsequent **defragmentation**…
- **Range of permitted IP datagram sizes**
  - **Theoretically up to 64 kB**, lower in practice…
  - Since it depends on **MTUs of real-world L2 technologies**
    - E.g.: Ethernet II (1500 B), Ethernet 802.3 with 802.2 LLC and SNAP (1492 B), Wi-Fi (2304 B), …

MTU Detection

Question: **How non-fragmenting MTU should be resolved?**

- Four strategies are basically possible for a given sender…

(1) **No Restrictions** (kind of optimistic approach)

- **Recommended size of IP datagrams is not limited in any way**
  - And so the maximal theoretical size is preserved
    - I.e., 64 kB minus IP headers
- **Suitable only when nothing better is achievable**
  - Since this approach will most likely always cause fragmentation

(2) **Guaranteed Minimums** (kind of pessimistic approach)

- It is guaranteed that certain **minimal IP datagram sizes** must be possible to transmit without fragmentation
  - Theoretically 68 B, in practice 576 B
    - Including IP headers in both cases, though

MTU Detection

(3) **Detection of Local MTU**

- L3 **MTU is derived from** L2 **MTU of a given network interface**
  - I.e., particular technology used by such an interface
- This approach is especially **appropriate for routers**
  - Since their interfaces are likely to use different technologies
  - As well as they should not be expected of anything else than **fulfilling their primary tasks only**
    - I.e., they should focus on **routing and forwarding**
    - Not advanced means of MTU discovery
- Unfortunately, even a single network can be heterogeneous
  - I.e., its **individual segments may use different technologies**
    - E.g., combination of Ethernet and Wi-Fi in not just home LANs
  - And so the interface MTU may not be valid within all segments

MTU Detection

(4) **Detection of Path MTU**

- Even when a datagram leaves our network unfragmented
  - It may still be subjected to fragmentation later on
  - Since **different networks can use different technologies**
- Therefore the **minimal permitted MTU on the way** could help
  - Such MTU can be detected using **Path MTU Discovery** process
- Unfortunately…
  - **Non-trivial overhead is required**
    - Because the detection process itself is not straightforward
  - **May not always work as expected**
    - Because of the **connectionless** nature of the IP protocol
    - I.e., individual datagrams may be routed differently
    - And so the detected path MTU may not actually be relevant

IPv4 Fragmentation

Fragmentation

- **Process of dividing IP datagrams into smaller fragments**
  - Each of which is then **routed and forwarded independently**
    - Without being reassembled sooner then at the destination
- Fragmentation can be performed by both…
  - End nodes acting as **senders** and **routers** on the way

Defragmentation

- **Process of IP datagram reassembling from its fragments**
  - There must exist a way…
    - How it is recognized that fragments **belong to each other** at all
    - And in which **mutual order** they are supposed to be combined
- Defragmentation can only be performed by…
  - End nodes acting as the final intended **recipients**

Fragmentation Process

Fragmentation principle

- **Datagram payload** is taken and **divided into smaller parts**
  - Each of which must have a suitable size
- **New IP datagram is constructed for each of these parts**
  - Its header is created as a **copy of the original header**
    - Where **certain fields are then affected accordingly**
- In particular…
  - **Fragmentation fields**
    - Generated, modified, or preserved as needed…
  - **Options**
    - Only the first fragment will take over all the original options
    - All the remaining fragments will contain **copied options** only
  - **IHL**, **Total Length** and **Header Checksum** fields are updated

Header Fields

Identification (16 bits)

- **Unique identification of a given group of fragments**
  - Unique means…
    - Unique value for a given **source and destination pair**
    - Within the **scope** of a node which generated this identifier
    - For the time the datagram will be active in the system
  - Undefined if not yet fragmented
- Identifier **life cycle**
  - **Generated during the very first fragmentation**
    - I.e., when fragmenting a not yet fragmented datagram
  - Preserved untouched in subsequent fragmentations

Header Fields

Fragmentation Flags (3 bits)

- Fixed 0 bit
- **Don't Fragment Flag**
  - **Requirement to prohibit fragmentation even if need be**
  - Possible values
    - 0 = fragmentation is permitted / 1 = prohibited
  - If prohibited but unavoidable nevertheless…
    - Such a datagram will need to be **discarded**
    - Sender is notified via **ICMP** **Destination Unreachable** message
- **More Fragments Flag**
  - **Flag indicating the very last fragment in a given group**
  - Possible values
    - 0 = the last fragment / 1 = more fragments follow

Header Fields

Fragmentation Offset (13 bits)

- **Expresses offset of the beginning of a given fragment**
  - I.e., its relative position with respect to the original whole
- Expressed in **integral multiples of 8 bytes**
  - And so fragment sizes must also be rounded to such multiples
    - Of course, with the exception of the very last fragment
- Observation
  - **It must be possible to further fragment datagrams that have already been fragmented**!
    - And so labeling of fragments with ordinal numbers instead of offset positions would not work for this purpose

Path MTU Discovery

Path MTU Discovery

- **Process allowing for detection of path MTU**
  - I.e., minimal MTU on a path across all involved networks
- Originally intended for routers
  - Nowadays **used by all modern end node operating systems**

Principle

- **Datagrams are iteratively sent in a loop**, step by step
  - Each time a certain particular **datagram size** is chosen
    - **Starting with the local MTU**
    - And **gradually decreasing** in subsequent iterations
  - **Don't Fragment Flag** is intentionally activated
    - I.e., set to value 1

Path MTU Discovery

Principle (cont'd)

- When **ICMP** Destination Unreachable response is received
  - We continue with **another attempt**
    - Where decreased datagram size will be used
  - The problem is that we were notified…
    - But **we were not provided with any particular suggestion**
    - I.e., **particular MTU that caused the problem**
    - And so we have to guess…
- Whole process ends when the intended destination is reached

Defragmentation Process

Defragmentation principle

- Individual fragments may not be delivered in **correct order**
  - And they actually do not need to be delivered at all
    - Any of them, independently on each other
- **Incoming fragments are therefore put into the buffer**
  - Only when we have all of them…
    - Because we know we received the very last of them
    - As well as there are no gaps in offsets and lengths
  - … **the original datagram is reassembled**
    - For which the fragments are ordered using their offsets
- **When any of the fragments is not delivered within a timeout**
  - Everything is lost
    - Since such fragments will simply not be delivered again
  - Sender is notified via an **ICMP Time Exceeded** message

Fragmentation Issues

Negative impact of fragmentation

- Whole concept **must be supported** by all involved nodes
  - Which in fact is, but…
- There is always a **non-trivial overhead**
  - Even if fragmentation actually did not occur at all
    - Because fragmentation headers are present nevertheless
- **Everything gets complicated**
  - Especially **defragmentation is complex and time demanding**
    - As well as more difficult to implement
- Impact of **reliability issues** is increased
  - **Loss or damage to any of the fragments** makes the entire original block unusable

Fragmentation Issues

Negative impact of fragmentation (cont'd)

- **Changes stateless behavior to stateful**
  - Since **waiting** is necessary until all fragments are received
  - As well as **timeouts** are introduced to handle non-deliveries
  - This is in conflict with design principles of the entire IP

$\Rightarrow$ **fragmentation should really be avoided whenever possible**

ICMPv4 Protocol

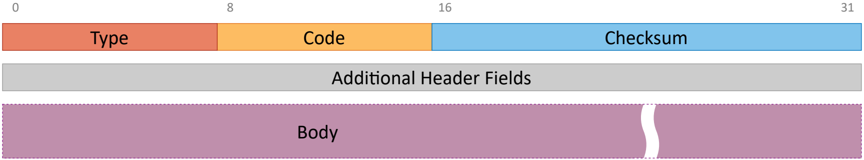
Internet Control Message Protocol (**ICMP**)

- **Auxiliary L3 protocol providing support to IPv4**
  - Allows to deal with **errors and non-standard situations**
    - Since IP alone is not capable of doing so
- **Types of messages**
  - **Error messages**
  - **Informational messages**: various queries, requests, replies, …
- **Scope of validity is not limited to just a single network**
  - And so ICMP messages need to be routed across networks
  - ICMP could thus work as yet another full-fledged L3 protocol
    - So that its messages would be inserted directly into L2 frames
    - But that would mean ICMP itself would need to be routable
  - And so instead, **ICMP messages are inserted into IP datagrams**
    - Which kind of (again) contradicts principles of layered models

ICMPv4 Messages

Message structure

- **Header** (64 bits)
  - Always fixed length, though **partially variable header fields**
- **Body**
  - May entirely be missing
  - Fixed or variable length
    - This length does not need to be explicitly remembered
    - Since it is derivable from the length of the entire IP datagram



ICMPv4 Messages

Header fields

- **Type** (8 bits)
  - **Main type** of a given ICMP message
- **Code** (8 bits)
  - Code describing a **particular subtype** of a given message type
- **Checksum** (16 bits)
  - **Checksum of the whole message**, not just its header
    - The same calculation mechanism as in case of IP itself is used
- **Additional header fields** (32 bits)
  - Depend on a particular message type
    - **Often unused** (but always present)

ICMPv4 Messages

Message **types and codes**

- Maintained by **IANA**
  - https://www.iana.org/assignments/icmp-parameters/
  - Current state (as of May 2021)
    - Almost $\approx$ 45 out of 256 types are used or reserved
    - Many of which are deprecated, though

Message **body**

- **Depends on a particular message type**
  - May entirely be missing as already outlined
- Often contains **beginning of the original IP datagram**
  - It means IP datagram which caused a given error message
  - In particular, its **full header and the first 64 bits of its body**
    - So that **source and destination** L4 **ports** are available, too
    - Which helps in correct recognition of the original datagram

Message Examples

Destination Unreachable (Type 3)

- Error messages sent when datagrams needed to be discarded
  - Since their further processing was not possible
    - Because of various particular reasons…
- **Network Unreachable** (Code 0)
  - Sent by routers on the way when…
  - **Network of the intended destination node is not reachable**
    - I.e., its distance in the routing table equals to infinity
    - Or the destination network is unknown at all
- **Host Unreachable** (Code 1)
  - Sent by inbound routers in the destination network when…
  - **Intended destination node is not reachable**
    - In case such a detection is possible at all

Message Examples

Destination Unreachable (Type 3) (cont’d)

- **Protocol Unreachable** (Code 2)
  - Sent by recipient nodes when…
  - **Designated transport protocol is not supported**
    - More precisely, payload type in **protocol field** is not supported
- **Port Unreachable** (Code 3)
  - Sent by recipient nodes when…
  - **Specified destination L4 port is invalid or not available**
    - I.e., it is not possible to perform datagram demultiplexing
- **Fragmentation Needed** (Code 4)
  - Sent by routers on the way when…
  - **Fragmentation is needed but was explicitly prohibited**
    - I.e, when the **Don’t Fragment Flag** was enabled
- …

Message Examples

Time Exceeded (Type 11)

- **Time to Live Exceeded in Transit** (Code 0)
  - Sent by routers on the way when…
  - **Datagram TTL was exceeded**
    - TTL value dropped to zero
- **Fragment Reassembly Time Exceeded** (Code 1)
  - Sent by recipient nodes when…
  - **Reassembling of a fragmented datagram was not possible**
    - Since not all fragments were received within a given timeout

Message Examples

Echo Request (Type 8, Code 0) and **Echo Reply** (Type 0, Code 0)

- **Allow for testing of reachability of nodes**
  - Sender sends an **Echo Request** message
  - Recipient responses with an **Echo Reply** message
    - At least should respond (it is compulsory)
    - But nowadays often does not because of security reasons
- Additional **header fields** are needed
  - **Allow to match corresponding pairs of requests and replies**
    - Since multiple requests may be sent in a row
  - **Identifier** and **Sequence Number**
    - **Unique identification and serial number given by a sender**
    - Particular implementation varies across individual systems
  - Both fields are preserved in replies, including message data
- Used by `traceroute` or `ping` utilities

Ping Tool

`ping` (backronym **Packet InterNet Groper**)

- **Diagnostic tool** allowing for testing of **reachability of nodes**
  - Together with **measured round-trip delivery times**
  - As well as basic **datagram loss statistics**

Basic principle

- **ICMP** Echo Request is sent to the intended destination
  - Actually a whole **series of requests** is sent, one by one
    - In order to make the detection and measurement more precise
- When **ICMP** Echo Reply response is received
  - Intended destination is reachable
- When **no response is received within a timeout**
  - Destination is considered as unreachable
    - Though it might just be unwilling to respond

Message Examples

Source Quench (Type 4, Code 0) (deprecated)

- **Feedback technique for** Congestion Control and Flow Control
  - When **routers or end nodes** reached their **capacity limits**
    - In terms of available buffer sizes, transmission capacity, …
  - Or even better, when they are just **approaching such limits**
- Principle
  - **Source nodes potentially causing the issues are informed**
    - I.e., respective sender or senders
  - So that **discarding of datagrams** is attempted to be avoided
- Observations
  - It is not possible to specify the **extent of congestion** problems
    - And so it is also not clear how the source nodes should react
  - Nor it is possible to revoke the original announcement

Message Types

Other interesting message types

- **Redirect** (Type 5)
  - **Signals incorrect or not optimal routing**
    - At the level of particular nodes or whole networks
- **Router Advertisement** (Type 9)
  - **Allows routers to reveal their existence** to end nodes
    - Using multicast to 224.0.0.1 (or broadcast when unavailable)
- **Router Solicitation** (Type 10)
  - **Allows end nodes to search for available routers**
    - Using multicast to 224.0.0.2 (or broadcast when unavailable)
- **Parameter Problem** (Type 12)
  - Messages representing **generic so far not covered problems**
- …

ARP

Address Resolution Protocol (ARP)

- Allows for **translation of IP addresses to hardware addresses**
  - For the purpose of **direct delivery** at L3
    - I.e., delivery within the context of a given network
- In particular…
  - We are about to **locally send an L3 IP datagram**
    - To the final recipient or just the first / next router on the way
    - **Intended recipient is expressed in terms of its L3 IP address**
    - I.e., in both the cases, we are provided with this address
  - Delivery of the datagram is, however, **executed using L2**
    - And L2 is only capable of working with L2 hardware addresses
    - Unfortunately, we only have the intended L3 IP address…
  - And so the corresponding L2 **address needs to be discovered**

ARP

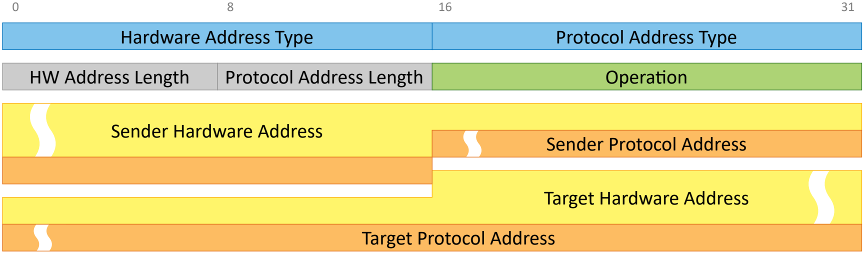
Address Resolution Protocol (cont'd)

- Basic idea
  - **Sender creates an ARP Request message**
    - Includes the queried IP address in this message
    - And **sends it to the whole network using** L2 **broadcast**
  - **Corresponding target node captures this request**
    - By matching its IP address with the queried one
    - **Creates an ARP Reply message with its hardware address**
    - And **sends it back via an ordinary** L2 **unicast**
- Observations
  - **Different technologies and addresses are used at** L2
  - As well as **different protocols and addresses are used at** L3
- $\Rightarrow$ it would be nice to handle them all in a unified way
  - ARP really is capable of such **universal applicability**

ARP Messages

Message structure

- All fields are compulsory, overall length is variable
  - Since individual **address fields have variable lengths**
- **ARP messages are encapsulated to L2 frames**
  - And so ARP as such belongs to the L3 network layer



Message Structure

Hardware Address Type (16 bits) and **Length** (8 bits)

- Describe the **type and length of** L2 **addresses**
  - I.e., identify a particular L2 technology
  - As well as length of its addresses in a number of bytes
- Types are maintained by **IANA**
  - https://www.iana.org/assignments/arp-parameters/
- Examples
  - **Ethernet** 10 Mb/s (type 1, length 6 bytes)
  - IEEE 802 Networks with **EUI-48** (type 6, length 6 bytes)
  - **EUI-64** (type 27, length 8 bytes)
  - **HDLC** (type 17, length 1 byte or more)
  - …

Message Structure

Protocol Address Type (16 bits) and **Length** (8 bits)

- Describe the **type and length of** L3 **addresses**
  - I.e., identify a particular L3 protocol
  - And similarly length of its addresses
- Types are (primarily) maintained by **IEEE RA**
  - **EtherTypes** were recycled for this purpose
  - http://standards-oui.ieee.org/ethertype/eth.txt
- Examples
  - **IPv4** (type `0x0800`, length 4 bytes)
  - **IPv6** (type `0x86DD`, length 16 bytes)

Message Structure

Operation (16 bits)

- Allows to distinguish individual **ARP operations**
- Codes are maintained by **IANA**
  - https://www.iana.org/assignments/arp-parameters/
  - **Request** (`1`), **Reply** (`2`), …

Sender Hardware Address and **Sender Protocol Address**

- `L2` and `L3` addresses of the sender
  - I.e., node sending a given request or reply

Target Hardware Address and **Target Protocol Address**

- `L2` and `L3` addresses of the indented recipient

Resolution Process

ARP Request message (operation code 1)

- **Type and length fields** are set according to the situation
- **Address fields** are filled in as follows…
  - Sender hardware and protocol addresses
    - Both are set according to the sender
  - **Target hardware address** is left undefined
  - **Target protocol address** is set to the **queried IP address**

ARP Reply message (operation code 2)

- Reply can be constructed directly from the received request
  - **Operation code** is changed from request to reply
  - **Source and target addresses are mutually swapped**
  - **Source HW address** is then set to the **resolved HW address**

Resolution Process

Resolution process has **significant overhead**

- Not just because **broadcast is required**
- It would also be inefficient to repeat requests over and over
  - And so **discovered mappings are cached**

ARP Cache

- **Table** with resolved **IP and hardware address bindings**
- Static **records** (e.g.: 192.168.1.255 → FF-FF-FF-FF-FF-FF)
- Dynamic **records**
  - Must be **periodically forgotten**
    - So that changes within the network can be reflected
    - Timeout can be 1 minute for end nodes, hours for routers
  - As well as **refreshed** to restrict new unnecessary queries
    - With the aim of optimizing the whole process even more

Resolution Process

Resolution steps

- **ARP Cache table is first consulted**
  - When the required **binding already exists**
    - It is simply fetched and the whole process ends
- **Otherwise** an **ARP Request message** is constructed
  - And sent to the whole network using L2 broadcast
- **Each and every node captures the request message**
  - And exploits the received information to update its cache
    - I.e., **adds a new binding** or **refreshes an already existing one**
- **Intended target node** (if any) furthermore…
  - Creates an **ARP Reply message**
  - And sends it to the original node using L2 unicast

Reverse ARP

Reverse Address Resolution Protocol (**RARP**)

- Allows for **translation of hardware addresses to IP addresses**
  - In terms of **assignment of an IP address to a given node**

Assignment process

- **RARP Request message** is constructed (**operation** code 3)
  - Message format remains the same as in the traditional ARP
    - Both **hardware address fields** are set to the known HW address
    - Both protocol address fields are left unused
  - **Request is then sent to the whole network via L2 broadcast**
- **RARP Server** captures this request
  - I.e., special host configured to serve such requests
  - **RARP Reply message** is constructed (**operation** code 4)
  - Reply is then sent back to the original node via L2 unicast

Reverse ARP

Drawbacks

- Very old and simple solution
- **RARP operates at** L3
  - Encapsulates its messages directly into L2 frames
  - And so **RARP server must be available in each network**
    - Since RARP messages cannot cross network boundaries
- Whole approach **cannot work without** L2 **broadcast**
- **Only fixed manually defined bindings are supported**
  - This is not sufficient from today's perspective
- **Additional information cannot be passed at all**
  - I.e., only IP address itself can be assigned
  - And not other (nowadays) essential information
    - E.g., netmask / CIDR prefix, router IP address, …

DHCP

Dynamic Host Configuration Protocol (**DHCP**)

- Newer solution dealing with the identified drawbacks
  - Based on **BOOTP** (**Bootstrap Protocol**)
    - Allow for IP address assignment, but its primary motivation was related to providing boot images to diskless workstations
- Advantages
  - One DHCP server can serve **multiple networks**
  - **Dynamic assignments** of addresses is possible
  - **Operates at** L7, uses UDP datagrams at ports 67 and 68
  - Allows for interchange of **additional information**
    - Netmask, routers, DNS servers, time zone, time servers, …
- Three **allocation strategies** are provided
  - **Manual**, **Automatic** and **Dynamic**

Allocation Strategies

Manual Allocation (also **Static Allocation**)

- Requesting client acquires a **predefined IP address**
  - Based on fixed **HW address** $\rightarrow$ **IP address bindings**
  - Created manually by the **network administrator** in advance
- As a consequence, **allocated address is always the same**
  - Which is suitable for network printers or similar devices

Automatic Allocation

- Requesting client acquires an **arbitrary IP address**
  - Chosen by the DHCP server itself from a given **address pool**
- Allocation is understood as **permanent**
  - It means the **binding is remembered the first time it is created**
  - So that the next time **the same address** can be granted again

Allocation Strategies

Dynamic Allocation

- Requesting client acquires an **arbitrary IP address**
  - Again chosen by the DHCP server from a given **address pool**
    - Of course, only currently unused addresses can be considered
- However, allocation is **temporary** only in this case…
  - Based on a **concept of lease**
    - I.e., only for a **limited period of time**
    - Which is specified at the moment of the allocation
- As a consequence…
  - **Different address may be provided each time!**
    - As well as one address can gradually be used by different nodes
- This has a **fundamental impact on IP address management**
  - Though it may not be apparent at first sight…

Lease Concept

Traditional approach

- Once assigned, **nodes have their addresses permanently**
  - In a sense of being their **owners or holders**
  - And so they can use them as long as they want to
    - I.e., for any length of time without any limitation
- This approach is **simple** on one hand
- But, unfortunately, **not flexible enough** on the other
  - Since **end nodes often roam from one network to another**
    - And so the whole traditional concept is no longer suitable for contemporary networks

Lease Concept

Newly introduced **concept of** lease

- Nodes act as **DHCP clients** in a sense of **temporary lessees**
  - **They must proactively take care of their IP addresses**
    - They are expected to perform **various tasks**
    - And so make transitions through **various states**

Period of lease

- Appropriate length depends on a particular situation
  - Shorter **periods**
    - **Higher flexibility**, **lower stability**, **higher overhead**
  - Longer **periods**… on the contrary
- In practice…
  - Hours, days, weeks, months, …

Client Actions

Allocation

- **Client does not yet have an IP address and asks for a lease**

Reallocation

- **Client does have an IP address and asks for its confirmation**
  - I.e., lease of the current address is still valid
    - And so there is actually no reason for such a request
- However, it is **voluntarily willing to accept a new address**
  - Since change at this moment would not cause any obstacles
  - E.g., because this node…
    - Has **just rebooted** or was **turned off for some time**

Client Actions

Renewal

- **Client has an IP address but its lease is approaching its end**
  - And so **extension of lease period is requested**
    - If granted, a new lease with the same address is in fact started
- First renewal attempt is initiated in 50% of lease time

Rebinding

- **Client asks a different server for the currently leased address**
  - Suitable when the original server became unavailable
    - I.e., when standard renewal could not be finished successfully
- First rebinding attempt is initiated in 87.5% of lease time

Release

- **Client returns its IP address before its lease expired**

IPv6 Protocol

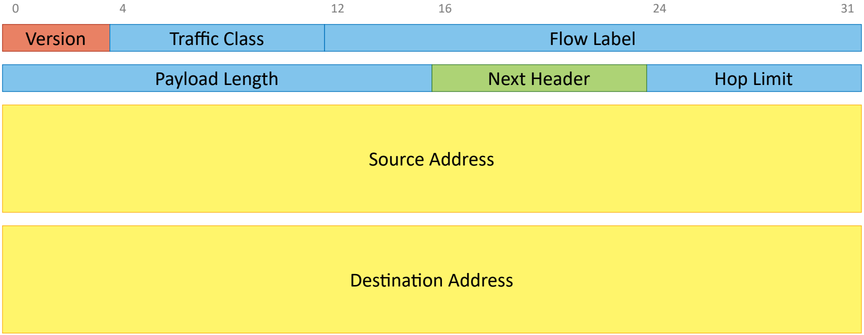
Internet Protocol version 6 (**IPv6**)

- **Differences** with respect to IPv4
  - **Larger IPv6 addresses**
    - 128 bits instead of just 32 bits
    - Together with 3 levels of routing (site / subnet / interface)
  - Simpler packet format
    - **Lower number of header fields**
    - Meaning and / or names of certain fields were changed
    - Some were removed entirely, e.g., **header checksum**
  - Concept of **extension headers**
    - Instead of IPv4 options
  - Different approach to **fragmentation**
  - Integrated **QoS support**
  - …

IPv6 Packets

Packet structure

- **Header chain**
  - **Main header** (40 bytes) and optional **extension headers**
- Optional **body**



Main Header Fields

Version (4 bits)

- Fixed value 6

Payload Length (16 bits)

- Overall size of **payload and extension headers** (if any)
  - Main header is not included

Hop Limit (8 bits)

- Analogy to IPv4 **Time to Live** field

Traffic Class (8 bits)

- Analogy to IPv4 **Type of Service** field
  - I.e., used for the purpose of **Differentiated Services**

Main Header Fields

Flow Label (20 bits)

- Allows to identify a particular **flow** = **group of related packets**
  - With the aim of treating them all in a similar way
    - E.g., with respect to QoS or other purposes
- In fact, **(Source Address, Flow Label)** forms the full identifier
  - Which allows to recognize such flows even at $\mathrm{L}3$
- In IPv4, **transport connection** identification would be needed
  - I.e., tuple (sender IP$_1$:port$_1$, protocol, recipient IP$_2$:port$_2$)
    - Which is less convenient when compared to IPv6
    - Since $\mathrm{L}4$ fields would need to be accessed in the payload

Extension Headers

Packet structure

- Whole packet is composed from a **chain** of…
  - **Compulsory main header**
  - **Arbitrary number of extension headers** (0 or more)
    - Each should **only be used at most once** (exception exists)
    - They should be used in a specific **recommended order**
    - So that processing of IPv6 packets by routers is simplified
  - **Optional body**
- Enumerated blocks are put into the packet one after another
  - **Each header contains the Next Header field**
    - Which allows to mutually chain the individual blocks
    - I.e., describe what the next block is supposed to contain

Extension Headers

Next Header (8 bits)

- Determines the **type of the next block** in a chain
  - I.e., type of the next **extension header** or **body payload**
  - Assuming that body (if any) must be placed at the very end
- Types (**Protocol Numbers**) are maintained by **IANA**
  - https://www.iana.org/assignments/protocol-numbers/
  - For simplicity, codes correspond to IPv4 analogies
- **Examples**
  - Extension headers: **IPv6 Fragmentation** (44), …
  - Payload protocols: **UDP** (17), **TCP** (6), **ICMPv6** (58), …
  - Special type: **IPv6 No Next Header** (59)
    - Suggests that noting follows
    - And even if something does follow, it must be ignored

IPv6 Fragmentation

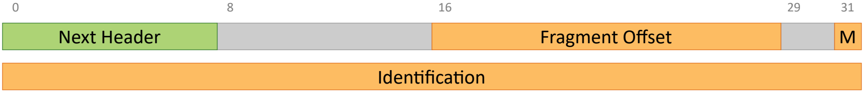
Fragmentation in IPv6

- Differences with respect to IPv4
  - **Only source nodes can perform fragmentation** (never routers)
    - So that they can focus on their primary objective
    - Excessive packets are then automatically discarded
  - All information is stored within the **Fragmentation Header**
    - I.e., it is only used when fragmentation really took place
  - **Guaranteed minimal non-fragmenting MTU** is 1280 B
    - Compared to just 68 B / 576 B in case of IPv4
  - **IPv6 Path MTU Discovery**
    - Basically the same idea as in IPv4, though differences exist…
    - **ICMPv6** **Packet Too Big** message is received instead
    - Includes value of the particular **MTU that caused the problem**

IPv6 Fragmentation

Fragmentation header (type 44)

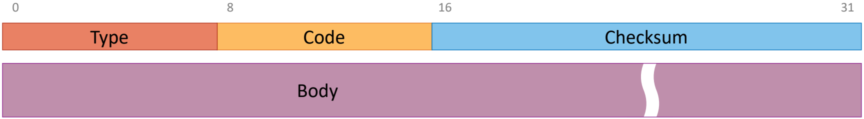
- **Next Header** (8 bits)
- **Fragment Offset** (13 bits)
  - **Relative to the end of the last non-fragmented header**
    - I.e., certain extension headers are fragmented, others not
    - Fragmentation header is then put in between these two groups
- **More Fragments Flag** (1 bit)
- **Identification** (32 bits)
  - The same principle as in IPv4, only larger range



ICMPv6

Internet Control Message Protocol version 6 (**ICMPv6**) (type 58)

- **Analogy to ICMPv4 for IPv4**
  - Basic principles are the same, though differences exist…
- **Longer part of the original IP packet** is preserved in body
  - As much as can be included not to exceed packet size 1280 B
    - So that fragmentation is avoided
- **Checksum calculation** also involves ICMP **pseudo-header**
  - With IPv6 source / destination addresses and other fields
- Slightly different generic **message structure**
- Different **types of particular ICMP messages**



Lecture Conclusion

IPv4 datagrams

- Header fields
  - Time to Live
  - Header Checksum
  - Protocol
  - …

IPv4 fragmentation

- Basic principles
- Avoidance strategies
- MTU detection approaches
  - Path MTU Discovery
- Issues

Lecture Conclusion

ICMPv4

- Destination Unreachable, Time Exceeded, …

ARP and **RARP**

- Translation of IP addresses to hardware addresses or vice versa

DHCP

- Manual, automatic, and dynamic **allocation strategies**
- Concept of **lease**, client actions

IPv6

- Main header, extension headers, body
- Fragmentation

ICMPv6